9. Modelling of Dust Voids in Electronegative Discharges under Microgravity

Abstract. Traces of molecular gases, like oxygen influence the size of the void observed microgravity experiments carried out at the International Space Station. These molecular gases produce negative ions via (dissociative) attachment. A considerable amount of negative ions changes the plasma properties, especially the potential distribution, and therefore the forces acting on a dust particle. We have investigated these phenomena by means of a 2D fluid model in which all the plasma parameters are calculated self-consistently. In this model we have included the possibility that negative ions are formed. By changing the attachment rate, we can control the electronegativity of the gas. Heating of the dust particle material by the recombining ions and electrons and subsequent heating of the gas is taken into account, as well as the heating of the background gas by ion-neutral collisions. As in electropositive discharges the resulting thermophoretic force, however, can be neglected at low peak-to-peak voltages compared to the other forces. Results from the fluid model show that indeed the presence of negative ions influences the evolution of the void and its final size. We will show how the relevant forces change with variation of the applied voltage in electropositive and electronegative discharges.

Submitted to: IEEE
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9.1 Introduction

Plasma crystal experiments performed under microgravity conditions have shown that dust particles usually arrange in a crystal like structure surrounding a stable void [1, 2]. The experiments are usually carried out in electropositive noble gasses as argon and krypton at static pressures around 40 Pa. Up till now the effects of electronegative gasses like oxygen, have not been studied in these experiments due to safety precautions on the International Space Station (ISS). We have developed a 2D argon-dust fluid model, which we have used previously to explain the appearance of the void in an argon discharge [3]. In this model we can also include the effect of attachment, producing negative ions, thus simulating a dust containing radio frequency (RF) discharge in the presence of an electronegative gas. The model contains a dust fluid part which has been described in [4]. It accounts for the presence of a large amount of dust, changing the plasma parameters. We have extended the model with an equation of state that has been described in [5], leading to a more sophisticated description of the crystalline regions. In this paper we describe the effect of negative ion formation on a discharge containing a significant amount of dust, by comparing the results for electropositive and electronegative discharges at different RF voltages.

9.2 Description of the model

9.2.1 Fluid model for the plasma species

To model the effect of an electronegative gas on a discharge containing a considerable amount of dust, we have used an extension of a previously described two-dimensional model [6], of which only the most important aspects will be summarized here. It consists of particle balance equations for the different species (electrons, ions and meta-stables) and an energy balance equation for the electrons. Ion-neutral collisions have been included to simulate a possible gas heating mechanism. For this we have used a simple approximation by assuming that the energy taken up from the electric field by the ions is dissipated locally in collisions with the gas [7]. This gas heating mechanism has been refined by taking the heating of the dust particle surface into account [4, 8]. The formation of negative ions is included to model the effect of negative ions on the formation of the void in a RF discharge. A discharge has been simulated in which an electronegative gas has been mimicked by adding attachment as a new process. Only the following reactions are considered:

\[ A + e \rightarrow A^+ + 2e, \]
\[ A + e \rightarrow A^-, \]

\[ A + e \rightarrow A^+ + 2e, \]
\[ A + e \rightarrow A^-, \]
\[ A^- + A \rightarrow A + A + e, \]
\[ A^- + A^+ \rightarrow A + A, \]

for the first process, ionization, the rate is calculated as a function of average electron energy by solving the two-term Boltzmann equation for the electron energy distribution for an argon plasma. For the second process, attachment by electrons, we have taken the attachment coefficient for a pure CF\(_4\)-plasma as given by the following expression [9]:

\[
k_{\text{att}}(\epsilon) = \begin{cases} 
0, & \text{if } \epsilon < 5.3; \\
2.0 \cdot 10^{-17} \cdot (\epsilon - 5.3)/(0.033 + \epsilon - 5.3), & \text{if } \epsilon \geq 5.3. \end{cases} \tag{9.1}
\]

So the attachment coefficient has a threshold energy of 5.3 eV and above this threshold it attains in a few tenths of eV a plateau value of 2.0 \(\cdot\) 10\(^{-17}\) m\(^3\)s\(^{-1}\). The third reaction is detachment of the negative ions, for this we have taken a rate coefficient of 1.0 \(\cdot\) 10\(^{-18}\) m\(^3\)s\(^{-1}\). The last reaction takes the recombination of positive and negative ions into account. We have chosen a recombination coefficient of 5.0 \(\cdot\) 10\(^{-13}\) m\(^3\)s\(^{-1}\). Changing the above mentioned coefficients offers a way to get more or less positive or negative ions in the discharge simulation. This mimics the the degree of electronegativity of the gas.

In the model the density balance for each species \(j\) is:

\[
\frac{dn_j}{dt} + \nabla \cdot \Gamma_j = S_j, \tag{9.2}
\]

where \(n_j\) is the particle’s density, \(\Gamma_j\) the flux of the species, and \(S_j\) the local sink or source.

The momentum balance is replaced by the drift-diffusion approximation for the particle fluxes,

\[
\Gamma_j = \mu_j n_j E - D_j \nabla n_j, \tag{9.3}
\]

with \(\mu_j\) and \(D_j\) the mobility and diffusion coefficient of species \(j\). \(E\) is the electric field.

For ions the characteristic momentum transfer frequency is only a few megahertz (MHz). To use the drift-diffusion approximation for positive and negative ions for RF frequencies higher than a few MHz the electric field in equation 9.3 is replaced by an effective electric field. Using this effective electric field \(E_{\text{eff}}\), inertia effects are taken into account. An expression for the effective electric field is obtained by neglecting the diffusive transport and inserting the expression \(\Gamma_i = \mu_i n_i E_{\text{eff}}\) in the simplified momentum balance

\[
\frac{d\Gamma_i}{dt} = \frac{en_i}{m_i} E - \nu_{m,i} \Gamma_i, \tag{9.4}
\]
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where \( \nu_{m,i} \) is the momentum transfer frequency of the ions given by

\[
\nu_{m,i} = \frac{e}{\mu_i m_i}.
\]  \(9.5\)

Here \( e \) is the elementary charge and \( m_i \) the mass of the ions. The effective electric field is then obtained by solving:

\[
\frac{dE_{eff,i}}{dt} = \nu_{m,i} (E - E_{eff,i})
\]  \(9.6\)

The same effective field is used for the positive and negative ions. The electric field \( E \) and potential \( V \) are calculated using the Poisson equation:

\[
\Delta V = -\frac{e}{\epsilon_0} (n_e - n_i - n_n - Q_d n_d),
\]  \(9.7\)

\[
E = -\nabla V,
\]  \(9.8\)

where \( \epsilon_0 \) is the permittivity of vacuum, \( n_e \) the electron density, \( n_i \) the positive ion density, \( n_n \) the negative ion density \( Q_d \) the number of electrons on a dust particle and \( n_d \) the dust density.

The electron energy density \( w_e = n_e \epsilon \) (i.e. the product of the electron density and average electron energy \( \epsilon \)) is calculated self-consistently from the second moment of the Boltzmann equation:

\[
\frac{dw_e}{dt} + \nabla \cdot \Gamma_w = -e \Gamma_e \cdot E + S_w,
\]  \(9.9\)

with \( \Gamma_w \) the electron energy density flux:

\[
\Gamma_w = \frac{5}{3} \mu_e w_e E - \frac{5}{3} D_e \nabla w_e,
\]  \(9.10\)

and \( \mu_e \) and \( D_e \) the electron mobility and electron diffusion coefficients. The term \( S_w \) in the electron energy balance equation is the loss of electron energy due to electron impact collisions, including excitation, ionization, attachment and recombination of electrons on the dust particle’s surface. Via the surface charge on the electrodes the plasma can be connected to an RLC circuit. Further details about the algorithms used to solve the above mentioned equations can be found in [6].

9.2.2 Implementing dust as a fluid

Charging of dust

When a dust particle exceeds a certain size it can collect more than one electron and be charged up to the floating potential relative to the surrounding plasma. This
potential depends on the local ion and electron density and energy distribution. For a spherical dust particle with a radius $r_d$, much smaller than the linearized Debye length, the Orbital-Motion-Limited theory (OML) predicts a positive ion and electron current, at equilibrium given by:

$$I_i = 4\pi r_d^2 n_i \sqrt{\frac{k_B T_i}{2\pi m_i}} \left( 1 - \frac{ev_{fl}}{k_B T_i} \right),$$

(9.11)

$$I_e = 4\pi r_d^2 n_e \sqrt{\frac{k_B T_e}{2\pi m_e}} \exp \left( \frac{ev_{fl}}{k_B T_e} \right).$$

(9.12)

Here, $n_e$ is the electron density, $n_i$ the positive ion density, $e$ the elementary charge, $k_B$ Boltzmann’s constant, $T_i$ the positive ion temperature, $T_e$ the electron temperature, $m_i$ the ion mass, $m_e$ the electron mass, and $V_{fl}$ the floating potential. All species are assumed to have a Maxwellian energy distribution. The influence of neighboring dust particles is neglected.

When the ions enter the plasma sheaths near the electrodes, they get a directed velocity $v_i$ due to the electric field. Therefore, we have replaced $k_B T_i$ in the expression for the ion current by the mean energy $E_i$, which is:

$$E_i = \frac{4k_B T_{gas}}{\pi} + \frac{1}{2} m_i v_i^2.$$  

(9.13)

Equation 9.13 is obtained by using the mean speed expression of Barnes et al [12] given by:

$$v_s = \left( \frac{8k_B T_{gas}}{\pi m_i} + v_i^2 \right)^{1/2}.$$  

(9.14)

By calculating $\frac{1}{2} m_i v_i^2$, equation 9.13 is obtained. The directed velocity $v_i$ is the drift velocity of the ions.

In the model the charge $Q_d = 4\pi \epsilon_0 r_d V_{fl}$ on the dust is calculated from the equilibrium of the currents in equation 9.11 and 9.12. The current of negative ions towards the dust particle’s surface is neglected, the negative ions do not have enough kinetic energy to overcome the negative floating potential of the dust particle.

The floating potential of the dust is assumed to be constant during an RF cycle. This assumption is justified by the fact that the currents towards the dust particle surface are too small to change the charge significantly during an RF cycle.

Recombination on dust particles

When a dust particle becomes negatively charged, it will attract positive ions, these will recombine with an electron that has to be replaced again by an electron
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from the discharge to maintain the floating potential. As a result the equilibrium fluxes of positive ions and electrons arriving at the dust surface will recombine and the released energy is used to heat up the dust particle surface [4, 8]. The electron flux (Eq. 9.12) results in a recombination rate:

\[
R = 4\pi r_d^2 n_d n_e \sqrt{\frac{k_B T_e}{2\pi m_e}} \exp \left( \frac{e V_{fl}}{k_B T_e} \right),
\]  

(9.15)

Forces acting on a dust particle

In a plasma dust particles undergo a wide variety of forces. Assuming that a dust particle is a perfect sphere the gravitational force can be written as:

\[
F_g = \frac{4}{3} \pi r_d^3 \rho_d g,
\]

(9.16)

where \( r_d \) is the dust particle radius, \( \rho_d \) is the mass density and \( g \) is the gravitational acceleration. For the often used melamine-formaldehyde dust particle \( \rho_d \) is approximately \( 1.51 \cdot 10^3 \) kg/m\(^3\).

When a dust particle has a velocity relative to the neutral gas, it will experience a drag force due to momentum transfer from/to the gas. This neutral drag force has been discussed in detail by Graves et al [11]. It can be approximated by,

\[
F_n = -\frac{4}{3} \pi r_d^2 n_n (v_d - v_n) v_{th} m_n,
\]

(9.17)

where \( n_n \) is the density of the neutral with mass \( m_n \), \( v_d \) the drift velocity of the dust particle, \( v_n \) the velocity of the gas and \( v_{th} \) the average thermal velocity of the gas. Because advection of the neutral gas is not included in the model, \( v_n = 0 \), this force will only be present as a damping force on the velocity of the dust particles.

Another force caused by momentum transfer is the ion drag. This force results from the positive and negative ion current that is driven by the electric field. It consists of two components. The collection force represents the momentum transfer of all the ions that are collected by the dust particle and is given by:

\[
F_i^c = \pi b_c^2 n_n v_s m_i v_i,
\]

(9.18)

where \( v_s \) the mean speed of the ions, \( v_i \) the ion drift velocity and \( b_c \) the collection impact parameter.

The second component is the orbit force given by:

\[
F_i^o = \sum_i 4\pi b_n^2 \frac{v_i}{2} \Gamma n_i v_s m_i v_i,
\]

(9.19)
with $b_{\pi/2}$ the impact parameter that corresponds to a deflection angle $\pi/2$ and $\Gamma$ the Coulomb logarithm.

$$\Gamma = \frac{1}{2} \ln \left( \frac{\lambda_L^2 + b_{\pi/2}^2}{b_C^2 + b_{\pi/2}^2} \right), \quad (9.20)$$

$\lambda_L$ is the linearized Debye length. The orbit force is summed for all ionic species. For the negative ions we have neglected the collection force because their kinetic energy is too low to overcome the negative floating potential of the dust. The ion drag is discussed in more detail by Barnes et al [12]. Previous calculations have shown that the ion drag should be enhanced with at least a factor 5 or the linearized Debye length in the Coulomb logarithm (Eq. 9.20) should be replaced by the electron Debye length, in order to generate a void [3]. We have used the electron Debye length in the calculations presented here. Khrapak et al [13] have studied cases where the ion drag force is underestimated by using the ion drag expression of Barnes with the linearized Debye length in the Coulomb logarithm. These cases are quite similar to ours. Lampe et al [14] have shown that collisions with the background gas may enhance the collection of ions.

Due to their charge, dust particles will experience an electric force. Daugherty et al [15] derived the following expression:

$$F_e = Q_d E \left( 1 + \frac{\kappa_r d}{3(1 + \kappa_r d)} \right), \quad (9.21)$$

where $Q_d$ is the charge on the dust particle, $E$ is the electric field and $\kappa = 1/\lambda_L$. In a discharge the dust particle radius is much smaller than the linearized Debye length, therefore the term between the bracket is approximately 1 and the electric force is given by:

$$F_e = Q_d E. \quad (9.22)$$

This expression holds for situations where the dust particles are not shielded from the plasma by positive ions trapped in orbitals around the dust particle [14]. In that case the particle plus ion cloud will behave as some kind of dipole.

When a temperature gradient is present in a discharge, for instance due to cooling or heating of the electrodes a third force driven by momentum transfer will occur. This force is called the thermophoretic force. Atoms impinging from the hot side have more momentum than their companions of the cold side, this can result in a force pointing in the direction $-\nabla T_{gas}$.

For large Knudsen numbers Talbot et al [16] derived the following expression:

$$F_{th} = -\frac{32}{15} \frac{v_d^2}{\nu_{th}} \left( 1 + \frac{5\pi}{32} (1 - \alpha) \right) \kappa_T \nabla T_{gas}, \quad (9.23)$$
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\( v_{th} = \left[ 8k_B T_{gas} / (\pi m) \right]^{1/2} \) is the average thermal velocity of the gas. \( \kappa T \) is the translation part of the thermal conductivity. \( \alpha \), the thermal accommodation coefficient of the gas is taken equal to 1.

To obtain a suitable expression for the flux of dust particles, we assume that the neutral drag force is in equilibrium with the sum of the other forces. This assumption is valid when the final steady state is approached, but should be relaxed, for instance, when the dust is injected at a high velocity. In that case the inertia of the dust should not be neglected. With the introduction of a momentum loss frequency and a mobility and diffusion coefficient for the dust particles given by:

\[
\nu_{md} = \sqrt{\frac{2}{k_B T_{gas}}} \frac{p_{tot}}{\pi r_d^2 \sqrt{8k_B T_{gas} \pi m_d}},
\]

(9.24)

where \( p_{tot} \) is the static pressure and \( m_d \) the dust particle’s mass,

\[
\mu_d = \frac{Q_d}{m_d \nu_{md}},
\]

(9.25)

\[
D_d = \frac{\mu_d k_B T_{gas}}{Q_d},
\]

(9.26)

it is possible to define a "drift-diffusion" expression for the flux of the dust particles,

\[
\Gamma_d = -\mu_d n_d \mathbf{E}_{eff} - D_d \nabla n_d - \frac{n_d}{\nu_{md}} \mathbf{g} + \frac{n_d m_i v_i}{m_d \nu_{md}} \left( \sum_{i=\text{neg}} \frac{4\pi b_i^2}{\nu_{md}} \mathbf{\Gamma}_i \right) + \sum_{i=\text{pos}} \frac{\pi b_i^2 \mathbf{\Gamma}_i}{\nu_{md}} - \frac{32}{15} \frac{n_d r_d^2}{m_d \nu_{md} v_{th}} \kappa_T \nabla T_{gas},
\]

(9.27)

and treat them with the same numerical procedures as the other charged particles in the fluid model. Because of the low mobility of the dust particles the effective field \( \mathbf{E}_{eff} \) is approximated by the time averaged RF field. The diffusion originates from the pressure gradient, \( k_B T_d \nabla n_d \). The Einstein relation couples the diffusion and the mobility coefficients, see equation 9.26.

The internal pressure of the crystal due to the inter-particle interaction has been included by means of an equation of state for the dust. Gozadinos et al [5] have obtained an expression for the equation of state for a crystalline structure of dust particles. The crystalline pressure is given by:

\[
P_{cr} = \frac{(1 + \beta \kappa)}{3 \beta} N_{nn} \Gamma P_g \exp(-\beta \kappa)
\]

(9.28)
where \( \Gamma = \frac{Q_d^2}{4\pi \varepsilon_0 \Delta k_B T_d} \) is the coupling parameter, \( \Delta = n_d^{-1/3} \) is the mean inter-particle distance, \( \kappa = \frac{\Delta}{\lambda_e}, P_g = n_d k_B T_d, N_{nn} \) is the number of nearest neighbours (\( N_{nn}=8 \) and \( \beta=1.09 \) for bcc lattices, \( N_{nn}=12 \) and \( \beta=1.12 \) for fcc and hcp lattices). We take only a fcc and hcp lattices into account in our simulations. With the above equation the effective diffusion coefficient for the crystalline regions becomes

\[
D_d = \frac{dP_n/dn}{m_d \nu_m}
\]  

Further details can be found in [5].

The drift velocity and the diffusion coefficient of the dust fluids are much smaller than those of the ions and electrons. Therefore it would require a large computational effort to achieve a steady state solution for the dust when it is followed during an RF cycle. We therefore have developed a method to speed up the convergence toward the steady state solution by introducing a different calculation cycle with a different time step for the dust. Our model thus consists of two calculation cycles. In the first one, the transport equations of the ions, electrons and the Poisson equation are solved during a number of RF cycles. During the RF cycles the dust does not move and its charge does not change. After that, the transport equation of the dust is solved with a greater time step, using the time averaged electric field, and electron and positive ion fluxes. During the second calculation, space charge regions are created, because the electron, positive and negative ion densities do not change. These space charge regions will lead to instabilities in the solution of Poisson equation and the electron transport. To solve this problem, we correct the artificially generated space charge by adapting the positive ion density distributions prior to the next series of RF cycles, in which the ion and electron density profiles adapt themselves to the new dust density profile. With this method the required speed-up is established. Both for the plasma species and for the dust fluids the transport equations are solved using the Sharfetter-Gummel exponential scheme [6]. To model the reactor, we have used a grid of 24 radial gridpoints times 48 axial gridpoints. We make use of a non-equidistant grid. The radial spatial resolution is 0.21 cm and the axial resolution between the electrodes is 0.09 cm. More details about the discretisation scheme can be found in [6].

### 9.3 Results and discussion

In this section the results, obtained with the 2D dust fluid model are presented. The PKE chamber used by Morfill et al has been modelled. The reactor is cylindrically symmetric. The simulation starts with a zero dust density profile. During the simulation the dust is injected from both electrodes by adding source terms in the dust particle balances for the first grid points below/above the electrodes. The
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injection rate is about 750,000 particles per second. Eventually a total amount of 1 million dust particles is reached, after that the sources are switched off. The electrodes are both driven by a radio-frequency power source at a frequency of 13.56 MHz. Two peak-to-peak voltages have been chosen, 300 and 600 volts. We have chosen these high values because simulations of electronegative discharges at lower peak-to-peak voltages than 300 volts crashed due to the low electron density. The pressure is 40 Pa. The dust particles have a diameter of 13.6 $\mu$m. Comparisons of the plasma parameters are made for electropositive and electronegative discharges.

Figure 9.1: Dust densities in m$^{-3}$ in different discharges and peak-to-peak voltages.
(a) Dust density in an electropositive discharge at 300 volts peak-to-peak, normalized with a factor $5.2 \cdot 10^{10}$.
(b) Dust density in an electronegative discharge at 300 volts peak-to-peak, normalized with a factor $3.1 \cdot 10^{10}$.
(c) Dust density in an electronegative discharge at 600 volts peak-to-peak, normalized with a factor $1.2 \cdot 10^{11}$.
Figures 9.1a-c show the steady state dust density profiles in different discharges varying the peak-to-peak voltage. In all cases a void (dust-free region) appears during the injection of the dust particles surrounded by a crystalline region as seen in the experiments [1]. After the injection of dust particles is stopped the dust particles move toward the reactor wall due to mainly the ion drag force and the thermophoretic force acting in the radial direction (Fig. 9.2). The forces exerted on the dust particles in the axial direction (Fig. 9.3) in combination with the equation of state speed up the movement of the dust particles toward the reactor wall. Figures 9.2a and 9.2b show that the thermophoretic force becomes more significant at higher peak-to-peak voltages. In the center of the discharge a dust-free region is formed. In figure 9.1b even the remains of the void are still visible.

![Figure 9.2: Forces acting on the dust particle at different peak-to-peak voltages in radial direction at z=0.021 m.](image)

(a) For a dust-free electronegative discharge at 300 volts peak-to-peak.
(b) For a dust-free electronegative discharge at 600 volts peak-to-peak.

*The solid line represents the ion drag force, the dotted line the electric force, the dashed line the thermophoretic force.*

Figures 9.4 and 9.5 show the time-averaged potential distribution $V(r,z)$ in the dust-free and the dusty discharges with and without negative ions. In all cases the potential has its maximum in the bulk of the plasma between the electrodes. Comparing the potential distributions, a significant change in the plasma potential can be observed. The slope of the plasma potential in the radial direction for the dusty discharges has increased compared with the dust-free cases. This results in a stronger radial electric field. This effect results from taking into account both the contribution of the charge on the dust (Fig. 9.6) in the Poisson equation and the recombination on the dust particle surface. The non-uniform charge distribution
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Figure 9.3: Forces acting on the dust particle at different peak-to-peak voltages in axial direction at r=0.

(a) For a dust-free electronegative discharge at 300 volts peak-to-peak.
(b) For a dust-free electronegative discharge at 600 volts peak-to-peak.

The solid line represents the ion drag force, the dotted line the electric force, the dashed line the thermophoretic force.

Figure 9.4: Time-averaged electric potentials in volts in different dust-free discharges.

(a) In an electropositive discharge at 300 volts peak-to-peak.
(b) In an electronegative discharge at 300 volts peak-to-peak.
Figure 9.5: Time-averaged electric potentials in volts in different dusty discharges.
(a) In an electropositive discharge at 300 volts peak-to-peak.
(b) In an electronegative discharge at 300 volts peak-to-peak.

is the result of the spatial distribution of the ions, electrons and electron energy. The enhanced ion density in the dust cloud reduces the dust charge.

Comparing figures 9.7a and 9.7b, shows a lower electron density for an electronegative discharge due to the formation of negative ions. Another effect that can also be observed is the weaker radial electric field in the electronegative discharge resulting in a radially broader electron density profile. After the injection of dust particles, the radial electric field becomes stronger, resulting in a more confined electron density profiles (Fig. 9.8). Due to a higher electron temperature in the case of an dusty electropositive discharge the ionization rate increases resulting in slightly more electrons in the center (Fig. 9.9a). For an dusty electronegative discharge the electron density (Fig. 9.9b) shows even a small decrease due to a lower electron temperature in the center of the discharge. Comparing the negative ion density profiles (Fig. 9.10a and 9.10b) shows an increase of the negative ions density in the center of a dusty discharge due to a steeper electric potential profile (Fig. 9.5b). Due to a lower electron density in an dust-free electronegative discharge, the electrons can gain more energy from the larger oscillating electric field, this gives rise to a higher electron temperature compared to a dust-free electropositive discharge (Fig. 9.11a and 9.11b).

Comparing the positive ion density profiles for dust-free discharges with and without the formation of negative ions (Fig. 9.12a and 9.12b), shows a significant increase of the positive ion density in an electronegative discharge, this is due to the formation of negative ions which have to be compensated by the positive ions to maintain quasi-neutrality in the bulk of the plasma. For the dusty discharges
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Figure 9.6: Number of electrons on a dust particle in different dusty discharges.
(a) In an electropositive discharge at 300 volts peak-to-peak.
(b) In an electronegative discharge at 300 peak-to-peak.

Figure 9.7: Time-averaged electron densities in m$^{-3}$ in different dust-free discharges.
(a) In an electropositive discharge at 300 volts peak-to-peak, normalized with a factor $1.7 \cdot 10^{16}$.
(b) In an electronegative discharge at 300 volts peak-to-peak, normalized with a factor $0.9 \cdot 10^{16}$. 
Figure 9.8: Time-averaged electron densities in $m^{-3}$ in different dusty discharges.
(a) In an electropositive discharge at 300 volts peak-to-peak, normalized with a factor $1.9 \cdot 10^{16}$.
(b) In an electronegative discharge at 300 volts peak-to-peak, normalized with a factor $0.8 \cdot 10^{16}$.

Figure 9.9: Time-averaged electron temperature in $K$ in different dusty discharges.
(a) In an electropositive discharge at 300 volts peak-to-peak.
(b) In an electronegative discharge at 300 volts peak-to-peak.
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Figure 9.10: Time-averaged negative ion densities in m$^{-3}$ in different discharges.
(a) In a dust-free electronegative discharge at 300 volts peak-to-peak, normalized with a factor $1.8 \cdot 10^{16}$.
(b) In a dusty electronegative discharge at 300 volts peak-to-peak, normalized with a factor $2.0 \cdot 10^{16}$.

Figure 9.11: Time-averaged electron temperature in K in different dust-free discharges.
(a) In an electropositive discharge at 300 volts peak-to-peak.
(b) In an electronegative discharge at 300 volts peak-to-peak.
the positive ions (Fig. 9.12a and 9.12b) are more confined due to a stronger confinement of the electrons and negative ions. In the center of the dusty discharges also slight increase of the positive ion density (Fig. 9.13a and 9.13b) can be observed. For the dusty electropositive discharge this effect can be attributed to a higher electron temperature (Fig. 9.11a and 9.9a) resulting in an larger ionization rate. For an electronegative plasma the increase is due to a better confinement of the negative ions (quasi-neutrality).

![Figure 9.12: Time-averaged ion densities in m^−3 in different dusty-free discharges.](image)

(a) In an electropositive discharge at 300 volts peak-to-peak, normalized with a factor $1.7 \cdot 10^{16}$.

(b) In an electronegative discharge at 300 volts peak-to-peak, normalized with a factor $2.7 \cdot 10^{16}$.

Figures 9.14a and 9.15a show the gas temperature for an electropositive and electronegative dusty discharge. The gas temperature profiles in the dusty plasmas have two maxima of 290 K in the sheaths, which is about 17 K higher than the reactor wall temperature that is kept at 273 K. No significant differences can be observed between the two gas temperature profiles. In figures 9.14a and 9.15a the dust particle (surface) temperature is shown for an electropositive and electronegative dusty discharge, it can be observed that a dust particle would get a maximum temperature in the center of the plasma if it would settle there. This is due to the maximum in the ion and electron density in the middle of the discharge, giving a maximum recombination energy flux towards the dust particles surface. Note that the difference between the gas and dust particle surface temperature would be about 72 K if the particle is at the center of the discharge.
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Figure 9.13: Time-averaged ion densities in $m^{-3}$ in different dusty discharges.
(a) In an electropositive discharge at 300 volts peak-to-peak, normalized with a factor $1.9 \cdot 10^{16}$.
(b) In an electronegative discharge at 300 volts peak-to-peak, normalized with a factor $2.8 \cdot 10^{16}$.

Figure 9.14: Gas (a) and dust particle material temperature (b) in a dusty electropositive discharge in $K$ at 300 volts peak-to-peak.
9.4 Conclusions

Modelling results have shown significant differences in plasma parameters, like the electron densities and ion densities, between electropositive and electronegative dusty discharges. This results in different steady state solutions for the dust density profile. The positive ion density at the center of a dust-free discharge becomes 50% higher in an electronegative discharge compared to an electropositive discharge at the same pressure and peak-to-peak voltage. This significant increase in positive ion density can be attributed to the formation of negative ions and maintaining quasi-neutrality in the bulk of the plasma. The electron density decreases with a factor 2 for the electronegative case. Introducing dust particles at the chosen peak-to-peak voltages results for both discharges in the formation of a dust cloud close to the reactor wall. At these positions the influence of this dust cloud on the plasma parameters is very small due to the negligible recombination on the dust particle surface. The results indicate a smaller void in an electronegative discharge than in an electropositive discharge. This can be attributed to the fact that the electric potential in an electronegative discharge is somewhat lower and flatter at the center. The thermophoretic force becomes more significant at higher peak-to-peak voltages.

Acknowledgments

This work was performed under the Euratom-FOM Association Agreement with financial support from the Netherlands Organisation for Scientific Research (NWO), the Netherlands Organisation for Energy and the Environment (NOVEM), and Eu-
ratom.
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