Modeling Dusty Plasma Discharges of Noble Gases Using a Self-Consistent Fluid Model

Diana Bolser, Victor Land, Lorin Matthews, and Truell Hyde, *Center for Astrophysics, Space Physics, and Engineering Research, Baylor University, Waco, TX 76798-7316, USA*

***Abstract*—Complex plasmas, which consist of electrons, ions and charged micro-particles, are an interesting and largely unexplored state of matter. One of the most intriguing phenomena in complex plasmas is the formation of dust-free voids in micro-gravity experiments. In order to achieve an isotropic dusty plasma system, this void must be closed. Using a self-consistent fluid model to simulate plasma behavior, the present study aims to investigate radio frequency (RF) discharges of helium, neon, and xenon gases, in addition to the already well understood argon discharge, at varying powers and pressures. The scope of this study is two-fold, in that dust-free discharges and dusty discharges will be modeled. The expansion of the fluid model to include other noble gases represents an important development in numerical modeling of complex plasmas.**

***Index Terms*—complex plasma, micro-gravity experiments, numerical modeling, radio frequency discharge, void**

I. Introduction

Complex plasmas are a collection of electrons, positively charged ions, neutral atoms, and charged micro-particles called dust. Dusty plasmas occur naturally in space and fusion processes on Earth [1]. Industrial plasma applications, particularly silicone wafer processing, are also affected by dust [2]. Recently, different numerical tools have been developed to simulate the effects of dust on the plasma environment [3-4]. However, these methods are limited by their failure to account for the influence of highly concentrated dust particles on the discharge. The model applied in this study uses a fully self-consistent approach, which solves the coupled dust-plasma system.

In complex plasma experiments on Earth, the dust is confined by gravity; however, micro-gravity experiments produce a large dust-free void [5-6]. The problem of void formation has been well studied in argon plasmas [7-8]. However, the next generation of micro-gravity experiments will be conducted with helium, neon, and xenon discharges. This study models these discharges and corresponding void behavior by extending the existing fluid code. The aim is to provide a roadmap for future experiments that will describe the conditions necessary for void closure for all the noble gases used in this study. The structure of this paper is as follows: section II discusses the theory of dusty plasmas, section III describes the fluid model, section IV presents the results for dust-free discharges and dusty discharges in micro-gravity, and section V makes some comments regarding the future of dusty plasma research.

II. Theory

A. Dust Particle Charging

Complex plasmas are characterized by the presence of dust particles that, when immersed in plasma, acquire an overall negative charge due to the capture of electrons and ions from the plasma. The surfaces of dust particles act as recombination centers for plasma particles. Orbital motion limited (OML) theory [9] can be used to calculate the charging currents by applying conservation of energy and angular momentum. This theory follows the trajectories of plasma particles in the potential around the dust particle. Charge equilibrium is achieved when the net current to the particle is zero. As a result of dust particle charging, there exists a high electrostatic energy of interaction between individual dust particles, which explains the appearance of ordered crystal structures observed in dusty plasmas. Experimentally, such structures are observed in the sheath of RF discharges where a strong electric field can counteract gravity and induce particle levitation [10].

B. Forces Acting on a Dust Particle

Dust particles introduced into a plasma will be influenced by such forces as gravity, the thermophoretic force, the electrostatic force, the neutral drag force, and the ion drag force.

On Earth, particles are accelerated by the force of gravity

$$F = \frac{4\pi\rho R^3 g}{3} \tag{1}$$

with ρ the mass density of a dust particle and R the radius of a spherical dust particle.

Collisions between cold atoms and hot ions result in local heating of the neutral background gas, thereby introducing a temperature gradient. The heated neutral atoms impart momentum to the dust through collisions. More collisions will occur on that side of the dust particle facing the hotter part of the background gas; therefore, dust particles experience a net force, the thermophoretic force, against the temperature gradient.

$$F = -\frac{32}{15}\frac{R^2}{v}\kappa\nabla T_n \qquad (2)$$

with v the velocity of, κ the thermal conduction coefficient, and T_n the background gas temperature.

The charged dust particles interact with electric fields through the electrostatic force

$$F = Q_d E \qquad (3)$$

with Q_d the dust charge and E the electric field.

The neutral drag force results from the resistance of the background gas molecules to the motion of a dust particle

$$F = -\frac{4}{3}\pi R^2 n_n m_n v_d \qquad (4)$$

travelling at velocity v, with n_n the density and m_n the mass of the background gas.

The ion drag force is given by

$$F = \pi(b_c^2 + b_s^2)n_+ m_+ v_+ v_s \qquad (5)$$

with b_c the cross-section for ion collection and b_s the cross-section for ion scattering, n_+ the ion density, m_+ the ion mass, v_+ the ion drift velocity, and v_s the mean ion speed.

The ion drag force depends on the shielding of the dust particle by the plasma particles. Typically, the heavy ions are surrounded by electrons, which cause the potential around the positively charged ions to drop off in a phenomenon referred to as shielding. A similar effect occurs in complex plasmas with the massive, negatively charged dust particles surrounded by ions and electrons. The ion drag force becomes relevant when studying those dust-free regions known as voids. At the boundary of the void, the electric field is directed outward from the center, thus the electrostatic force points inward. The existence of a void suggests that the ion drag force opposes the electric field force and repels dust particles from the center of the discharge [11].

III. MODEL

A complete description of the fluid model has already been given elsewhere [12-13]. The model includes dust charging, recombination of plasma on the dust, and the corresponding heating of the dust. From the forces acting on the dust particle, the problem of dust transport through the plasma can be solved. The plasma densities are solved by using the drift-diffusion approximation, which provides an expression for the flux, Γ, consisting of a drift term and a diffusive term

$$\frac{\partial n_{+,e}}{\partial t} + \vec{\nabla}\cdot\vec{\Gamma} = S \qquad (6)$$

$$\vec{\Gamma} = \mu n_{+,e}\vec{E} - D\vec{\nabla} n_{+,e} \qquad (7)$$

with n_e the electron density, μ the mobility coefficient, and D the diffusion coefficient. The sources and sinks, S include ionization, excitation, and recombination of electrons and ions on the surfaces of dust particles. The electric field is calculated using the Poisson equation

$$\Delta V = -\frac{e}{\varepsilon_0}(n_e - n_+ + Z_d n_d) \qquad (8)$$

$$E = -\nabla V \qquad (9)$$

with n_d the dust density, Z_d the dust charge number, ε_0 the permittivity of free space, e the electron charge, and V the potential. As the ions are too massive to follow the rapidly oscillating RF cycle, an effective electric field is calculated.

The model also solves the electron energy balance equations by using a similar drift-diffusion approach

$$\frac{\partial w_e}{dt} + \vec{\nabla}\cdot\vec{\Gamma} = J\cdot E + S \qquad (10)$$

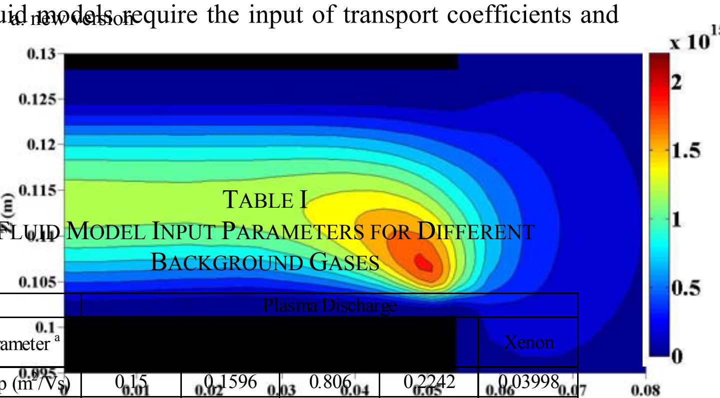
$$\vec{\Gamma} = -\frac{5}{3}\mu w_e E - \frac{5}{3}D\vec{\nabla} w_e \qquad (11)$$

with w_e the electron energy density and $J\cdot E$ the Ohmic heating of electrons in the electric field.

Fig. 2. Electron density (/m3) profiles of argon discharge at 200mT pressure and 1W power. The black boxes represent the top and bottom electrodes.

Fluid models require the input of transport coefficients and rate this by coe wer con moc the gas tem liter

a. new version



Collision cross-section data were generated by Bolsig+ and tabulated for mean electron energies ranging from 0eV to 15e ioni ion and con heat the dust

b. original version

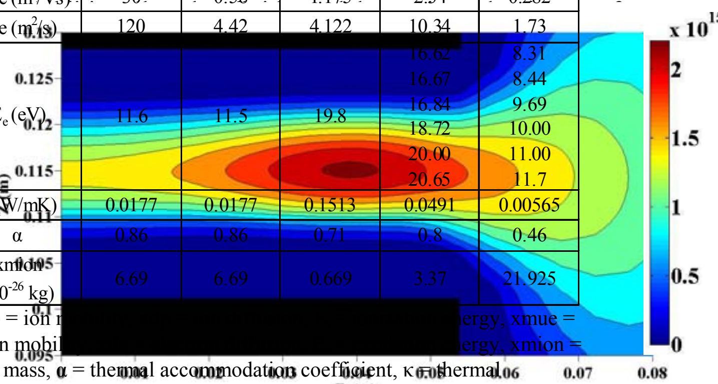


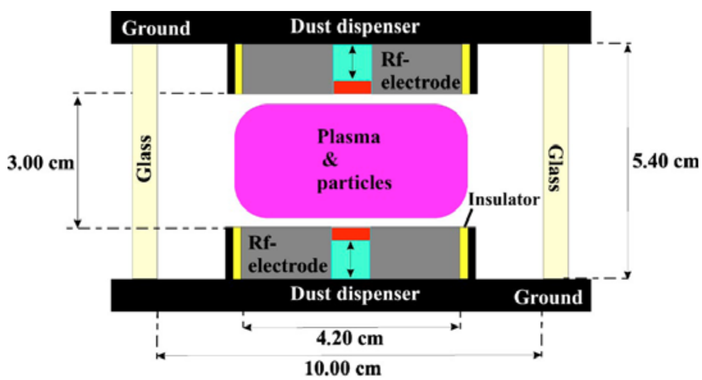
TABLE I
FLUID MODEL INPUT PARAMETERS FOR DIFFERENT BACKGROUND GASES

Parameter [a]	Plasma Discharge				
	[illegible]	[illegible]	[illegible]	[illegible]	Xenon
xmup (m^2/Vs)	0.15	0.1596	0.806	0.2242	0.03998
xdp (m^2/s)	0.004	0.00106	0.0209	0.00418	0.001035
E_i (eV)	15.7	15.8	24.58	21.56	12.12
xmue (m^2/Vs)	30	0.58	1.175	2.34	0.282
xde (m^2/s)	120	4.42	4.122	10.34	1.73
E_e (eV)	11.6	11.5	19.8	16.62 16.67 16.84 18.72 20.00 20.65	8.31 8.44 9.69 10.00 11.00 11.7
κ (W/mK)	0.0177	0.0177	0.1513	0.0491	0.00565
α	0.86	0.86	0.71	0.8	0.46
xmion (10^{-26} kg)	6.69	6.69	0.669	3.37	21.925

[a] xmup = ion [illegible]ergy, xmue = electron mobil[illegible]ergy, xmion = atomic mass, α = thermal accommodation coefficient, κ = thermal conduction coefficient

For comparative purposes and to maintain consistency, the existing argon model was updated. Input parameters for argon, helium, neon, and xenon are summarized in Table I. Parameters for power and pressure were set at 1, 2, and 4W and 100, 200, and 400mT, respectively, for a total of nine unique discharge conditions. Due to symmetry, the fluid code only models half of the cell. Initially, the model considered dust-free discharges. After the dust-free discharges converged, melamine formaldehyde dust particles with a radius of 4.445μm were added to the micro-gravity systems. Push-pull mode was engaged to power both the top and bottom electrode. The volume dimensions of the dust-free environment mimic those of a modified Gaseous Electronics Conference (GEC) reference cell, while the geometry of the dusty discharges is the same as that used for Plasmakristall experiments (PKE) [23] aboard the International Space Station (Fig. 1).

Fig. 1. A diagram of the PKE chamber.



IV. Results and Discussion

A. Dust-Free Discharges in the GEC Cell

The fluid model for argon was updated using the procedure outlined in section II. The electron density and ion density profiles in the new version maintained a similar global pattern as the original, but peaked at lower maximums, shifting radialy and down towards the electrode (Fig. 2). Similar shifting behavior was also observed in helium, neon, and xenon for increasing pressure. Also, the new argon version produced an unexpected positive dc bias of 5V and 10V at 200mT pressure 2W power and 400mT pressure 4W power, respectively, compared to -80V and -120V originally. The neutral gas temperature was cooler in the new version, which indicated less ion density and consequently, agreed with the shifted ion density profile.

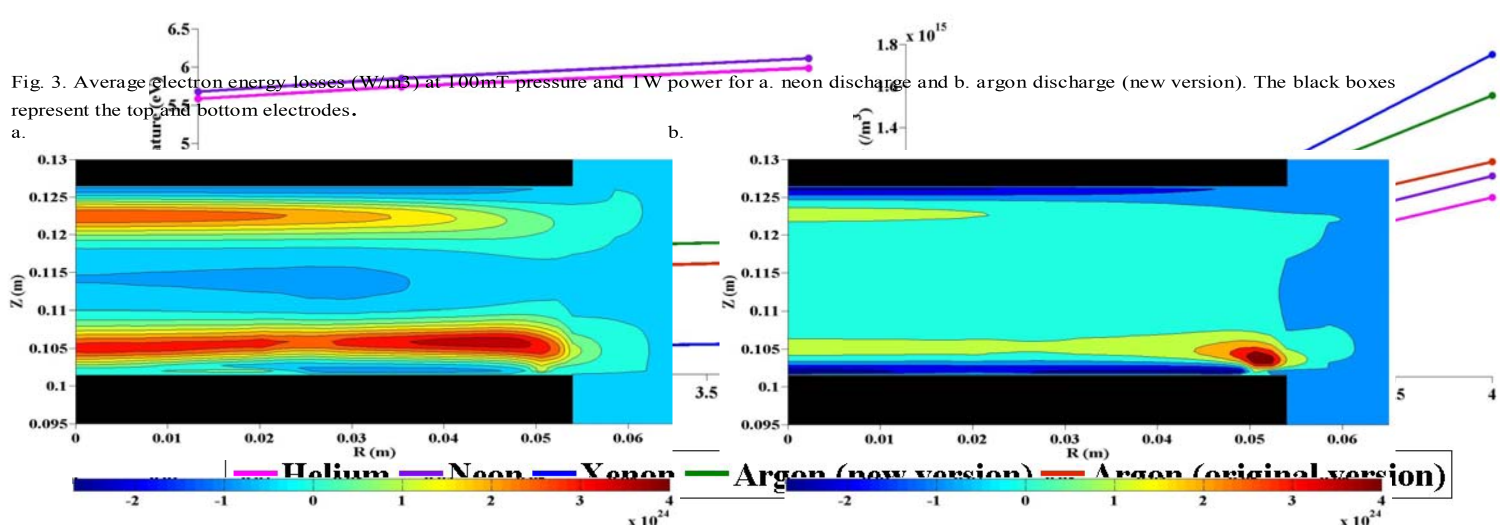
Neon and xenon have six excitation levels compared to argon and helium that only have one. Moreover, all of the excitation levels are at lower energies than that required for ionization. Therefore, energy losses for neon and xenon extended further into the bulk and were not contained to locations of greatest average ionization (Fig. 3).

All the discharges showed the same pattern of higher mean electron temperature for low pressures and high powers (Fig. 4a). Most electron heating occurred in the regions of strongest electric fields, located in the sheaths. This can be explained by the relationship between the electric field and the potential dictated by (9), the gradient having the steepest slope in the sheath region. Increasing power increases the RF amplitude, thereby causing stronger electric fields. Neon and helium reached higher temperatures as a consequence of their large ionization and excitation energies, which restricts electrons from spending their energy on inelastic processes. Xenon achieved very low electron temperatures because it has the lowest energy threshold, and therefore electrons can easily lose energy in inelastic processes.

Near the edge of the electrodes, the electric field is directed towards the outer walls. This electric field accelerates ions towards the walls. All the ion heating occurred in the sheath regions for every discharge in this study. Electrons accelerated in the electric field gain energy necessary for inelastic processes like excitation and ionization. The greatest energy losses corresponded to locations of greatest electron heating, since electrons must build up large amounts of energy to participate in inelastic collisions. Increasing pressure increases the density of neutral atoms and thus the probability of collisions of electrons with neutral atoms, so heating becomes

Fig. 4. a. Mean electron temperature at 200mT pressure. b. Mean electron density at 200mT pressure.

Fig. 3. Average electron energy losses (W/m3) at 100mT pressure and 1W power for a. neon discharge and b. argon discharge (new version). The black boxes represent the top and bottom electrodes.



more localized.

At high powers, xenon achieved the highest electron density, followed by argon, neon, and helium (Fig. 4b). This trend approximately follows increasing electron mobility coefficients.

B. Dusty Discharges in Micro-gravity

Dust-free regions were observed in the centers of all the discharges; however, the high powers used in this study prevented helium from forming a complete void (Fig. 5a), whereas neon, at identical experimental settings, successfully produced a whole void (Fig. 5b). Future experiments on void formation in micro-gravity should use less than 1W of power. Furthermore, there was less average ionization and dust charging for helium than neon. Whereas the ionization was focused on the center of the helium discharge, ionization in neon was contained to bands near the electrodes. It is apparent that changing the electron and ion coefficients greatly affects the interaction of the plasma with the dust resulting in different void behavior.

V. CONCLUSION

This study expands on previous fluid models by including other noble gases like helium, neon, and xenon in addition to the traditional argon discharge. An updated version of the original argon code was tested and compared to existing data. A comparative evaluation of dust-free discharges in a GEC cell was accomplished. Furthermore, the model made successful predictions for dusty discharges under micro-gravity conditions. The problem of void formation was also addressed. Future studies of void closure will require additional power and pressure combinations, the ultimate goal being to generate a comprehensive two-dimensional plot of the pressures and potentials at which three-dimensional dust clouds in micro-gravity contain a dust-free void, or are void-free, for different carrier gases.

ACKNOWLEDGMENTS

Diana Bolser would like to thank the Baylor University Department of Physics and the Center for Astrophysics, Space Physics, and Engineering Research. Funding was provided by the National Science Foundation’s Research Experience for Undergraduates program.

REFERENCES

[1] V.N. Tystovich and J. Winter, "On the role of dust in fusion devices," Phys-Usp, vol. 41, pp. 815-822, 1998.

[2] V.E. Fortov, A.G. Khrapak, S.A. Khrapak, V.I. Molotkov and O. F. Petrov, "Dusty plasmas," Phys-Usp, vol. 47, pp. 447-492, 2004.

[3] O.S. Vaulina, S.A. Khrapak, A.P. Nefedov and O.F. Petrov. (1999, Nov). Charge-fluctuation-induced heating of dust particles in a plasma. Phys Rev E. 60(5), pp. 5959-5964.

[4] S.A. Khrapak and G.E. Morfill. (2002). Dust diffusion across a magnetic field due to random charge fluctuations. Phys Plasmas 9(2), pp. 619-623.

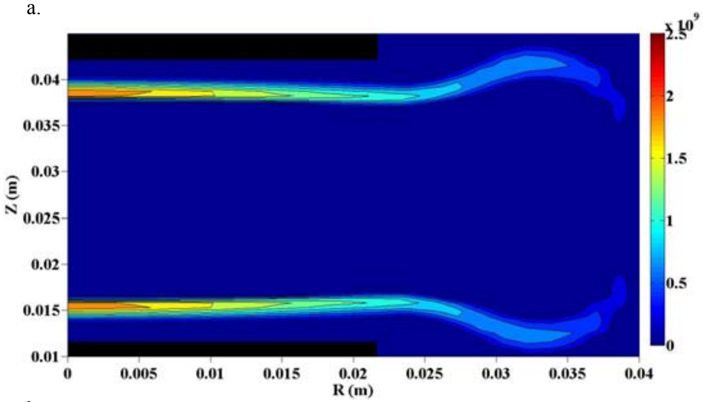
[5] M.R. Akdim and W.J. Goedheer. (2003, May). Modeling of self-excited dust vortices in complex plasmas under microgravity. Phys. Rev. E 67(5), pp. 056405.

[6] M.R. Akdim and W.J. Goedheer. (2001, Dec). Modeling of voids in colloidal plasmas. Phys Rev E. 65(1), pp. 015401.

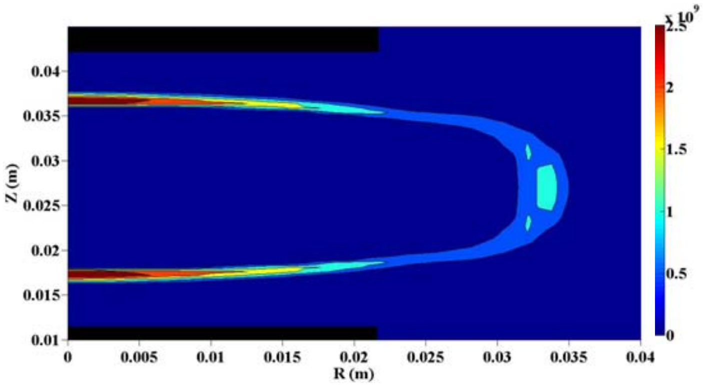
[7] M. R. Akdim and W. J. Goedheer. (2003, Jun). Modeling the effect of dust on the plasma parameters in a dusty argon discharge under microgravity. Phys. Rev. E 67(6), pp. 066407.

Fig. 5. Dust density (/m³) of a. helium discharge and b. neon discharge in micro-gravity at 100mT pressure and 1W power.

a.



b.



[8] A.D. Richards, B.E. Thompson and H.H. Sawin. (1987). Continuum modeling of argon radio frequency glow discharges. Appl. Phys. Lett. 50(9), pp. 492-494.

[9] J.E. Allen. (1992). Probe theory - the orbital motion approach. Phys. Scripta 45(5), pp. 497-503.

[10] J. H. Chu and L.I. (1994). Direct observation of coulomb crystals and liquids in strongly coupled rf dusty plasmas. Phys. Rev. Lett. 72(25), pp. 4009-4012.

[11] V. Land, "Computing the complex: Dusty plasmas in the presence of magnetic fields and UV radiation," 2007. Ph.D. thesis. Utrecht University. The Netherlands

[12] V. Land and W. J. Goedheer. (2006). Effect of large-angle scattering, ion flow speed and ion-neutral collisions on dust transport under microgravity conditions. New J. Phys. 8(1), pp. 8.

[13] V. Land and W. J. Goedheer. (2008). How to make large, void-free dust clusters in dusty plasma under micro-gravity. New J. Phys. 10(12), pp. 123028 (15pp).

[14] G.J.M. Hagelaar and L.C. Pitchford. (2005, Solving the boltzmann equation to obtain electron transport coefficients and rate coefficients for fluid models. Plasma Sources Sci. Technol. 14(4), pp. 722-733.

[15] V. Land, E. Shen, B. Smith, L. Matthews and T. Hyde. (2009). Experimental and computational characterization of a modified GEC cell for dusty plasma experiments. New J. Phys. 11(6), pp. 063024 (21pp).

[16] H.W. Ellis, M.G. Thackston, E.W. McDaniel and E. A. Mason. (1984). Transport properties of gaseous ions over a wide energy range, part III. Atomic Data and Nuclear Data Tables 31, pp. 113.

[17] H. Helm. (1976). The mobilities of atomic krypton and xenon ions in the 2P_1/2 and 2P_3/2 state in their parent gas. J. Phys. B: At. Mol. Phys. 9, pp. 2931-2943.

[18] L.A. Viehland and E.A. Mason. (1995). Transport properties of gaseous ions over a wide energy range, IV. Atomic Data and Nuclear Data Tables 60(1), pp. 37.

[19] G. Fan and J.R. Manson. (2008). Calculations of the energy accommodation coefficient for gas-surface interactions. ArXiv e-Prints.

[20] O.V. Sazhin, S.F. Borisov, and F. Sharipov. (2002). Accommodation coefficient of tangential momentum on atomically clean and contaminated surfaces. J. Vac. Sci. Technol. A 19(5), pp. 957.

[21] W.M. Trott, D.J. Rader, J.N. Castaneda, J.R. Torczynski and M.A. Gallis. (2008). Measurement of gas-surface accommodation. Presented at the 26th International Symposium on Rarefied Gas Dynamics, AIP Conf. Proc. 1084, pp. 621-628.

[22] A. Nefedov, G..E. Morfill, V..E. Fortov, H. M. Thomas and et. al., "PKE-Nefedov: plasma crystal experiments on the International Space Station," New J. Phys., vol. 5, pp. 33.1-33.10, 2003.