Numerical investigation on electrical characterization of a capacitive coupled radio-frequency plasma

H. Yao*[a,b], X. He[c], J. P. Chen[d] , Y.C. Zhang[e]
[a]School of Aerospace Engineering, Beijing Institute of Technology, Beijing, China 100081; [b]Navy Logistics Department of PLA, Beijing, China, 100841; [c]School of science, Hohai University, Nanjing, China, 210098; [d]Beijing Aeronautical Technology Research Center, Beijing, China 100076; [e]School of Science, Nanjing University of Science & Technology, Nanjing, China 210094

ABSTRACT

This paper presents the main electrical features of capacitive coupled radio-frequency (CCRF) discharges in gas. A two-dimensional, time-dependent fluid model was established. Capacitive coupled plasmas (CCP) were produced by applying radio-frequency voltage to a pair of parallel plate electrodes which are separated from the plasma by dielectric layers. The electron equation and the electron transport equations were solved and yielded the electron number density and electron temperature. The electrostatic field was obtained by the solution of the Poisson equation. The distribution of electron temperature and electron number density was studied under different conditions: radio-frequency applied voltages (V_{RF}=100-2000V), frequencies (f=3.0-40.68MHz), pressures (p=0.001-1torr), and gas species (O_2, Ar, He, N_2). The results show that electron number density presents a minimum near the electrodes, and presents a maximum between the positive and the negative electrodes. The distinguishing feature of CCP is the presence of oscillating sheaths near electrodes where displacement current dominates conduction current. These informations will help us to analyze the characters of CCP for application.

Keywords: Capacitive coupled plasmas, electron number density

1. INTRODUCTION

Over the years, many papers have been published on the features of capacitive coupled radio-frequency (CCRF) discharges in gas. The CCP is generally quite complex and difficult to numerical analysis. A wide variety of methods have been employed in this effort. These include full numerical solutions of the Boltzmann Equation [1], particle methods [2, 3] and fluid models [4-8]. In this paper, a model combines the fluid theory and kinetic theory [9-11] was adopted. This method keeps a good precision and reduces the amount of calculation. A two-dimensional, time-dependent fluid model was established. Capacitive coupled plasmas were produced by applying radio-frequency voltage to a pair of parallel plate electrodes which are separated from the plasma by dielectric layers. The simulation is mainly compared with various conditions for the distribution of electron temperature and electron number density.

2. SIMULATION FOR CAPACITIVE COUPLED PLASMA

2.1 Settings for Simulation

The calculated model is simplified in Figure.1. There are two electrodes with a distance of 5cm. The size of electrodes is 5cm, and they are located at the bottom of the discharge chamber which has a size of 5cm×10cm. The gas is poured into the chamber from the left edge, and has a flow rate of 0.2m/s. At the edge of the chamber, there is a gas extraction system with the same flow rate. One electrode is grounded and the other electrode is driven with RF voltage.

A plasma is a quasi-neutral mixture of charged species in which the density of negatively charged species is well balanced by the density of positively charged species. An equilibrium plasma is characterized by its temperature and pressure. RF plasma is thermodynamic equilibrium. Several processes occurring in the plasma lead to deviation from thermodynamic equilibrium.

*lushanyaohong@163.com

Third International Symposium on Laser Interaction with Matter (LIMIS 2014), edited by
Yury M. Andreev, Zunqi Lin, Xiaowu Ni, Xisheng Ye, Proc. of SPIE Vol. 9543, 95430Y

· doi: 10.1117/12.2182242

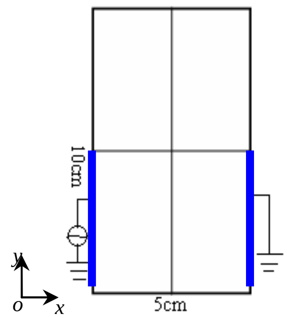

Figure 1. Simplified model for calculating the characteristics of capacity coupled plasma

The electron density and flow rate satisfied the continuity equation and momentum balance equation as following:

$$\frac{\partial n_e}{\partial t}+\frac{\partial (n_e v_e)}{\partial x}=k_i n_e n_n \tag{1}$$

$$\frac{\partial n_i}{\partial t}+\frac{\partial (n_i u_i)}{\partial x}=k_i n_i n_n \tag{2}$$

$$m_e n_e\left(\frac{\partial u_e}{\partial t}+u_e\frac{\partial u_e}{\partial t}\right)=-en_eE-\frac{\partial}{\partial x}(k_bT_en_e)-m_en_ev_{en}^{(e)}u_e \tag{3}$$

$$m_e n_e\left(\frac{\partial u_e}{\partial t}+v_e\frac{\partial u_e}{\partial t}\right)=-en_eE-\frac{\partial}{\partial x}(k_bT_en_e)-m_en_ev_{en}^{(e)}u_e \tag{4}$$

where n, u, m, T, and $v^{(e)}$ are the density, velocity, quality, temperature and collision frequency between electron and neutral particles, respectively. The subscript e, i and n are electron, ion and neutral atom. E is electric field intensity. k_i is the ionization rate coefficient. k_b is Boltzmann constant.

For electron, the flux density can be described by the drift diffusion approximation equation as following

$$\Gamma_i=-\rho D_i\nabla y_i+\rho y_i u_{di}+\Gamma_c \tag{5}$$

Where Γ_c is mass flux. y, ρ and D are the mass fraction, mass density and diffusion coefficient. u_d is the diffusion velocity, which can be written as

$$u_{di}=E(q_i\mu_i-\sum q_j\mu_j y_j) \tag{6}$$

where q and μ are electric charge and mobility. The temperature of ion is approximately equal to the temperature of neutral particle. They can be described by single enthalpy balance equation.

A Sharfetter-Gummel (exponential) scheme is used for numerical discretization of electron flux. This scheme assumes that electron flux T_e, mobility μ_e, and diffusion D_e, are constant between the mesh points. Then, the electron density n_e can be calculated exactly in the interval $0<x<L$ as follows:

$$\frac{n_e-n_0}{n_L-n_0}=\frac{\exp P(x)-1}{\exp P(x)L-1} \tag{7}$$

Where, n_0 and n_L are the values of n_e at $x=0$ and $x=L$ correspondingly, and P is a Peclet number, and $\nabla\varphi$ is potential drop between 0 and x. It can be seen that P is the ratio between convection and diffusion. The exact solution (7) is used to interpolate the values of variables from cell centers to faces.

The electrostatic potential φ is found using a time implicit Poisson solver:

$$(\nabla(\varepsilon + e\mu_e n_e \Delta t))\nabla\varphi(t+\Delta t) = e\left[\sum_i q_i n_i(t) - n_e(t)\right] - e\Delta t\left[(\nabla D_e)\nabla n_e + S\right] \quad (8)$$

The potential at the electrodes and metal walls is defined as a function of time. The potential at dielectric boundaries is found from the balance of the charged particle flux at a given point.

2.2 Results and discussion

Figure.2 shows the influence of varying radio-frequency applied voltages on the electron number density. The darker the color is, the higher the density is. And the values of the electron number density can be found in Fig.3. It can be seen that the electron number density increases with increasing applied voltage, seriously in the charge chamber except the positions nearby air inlet, outlet, and electrodes. A reason is that there is a higher ionizing rate of gas in the electronic field with a higher radio-frequency applied voltage.

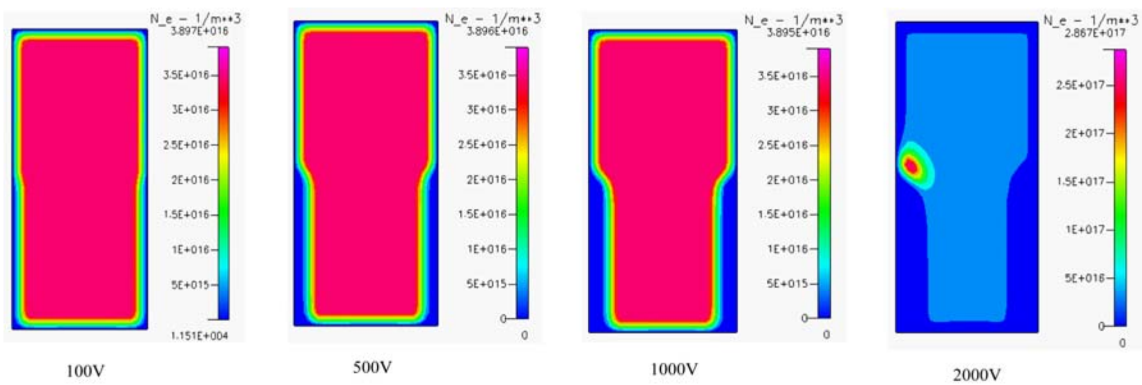

Figure2. The influence of varying radio-frequency applied voltages on the electron number density in chamber

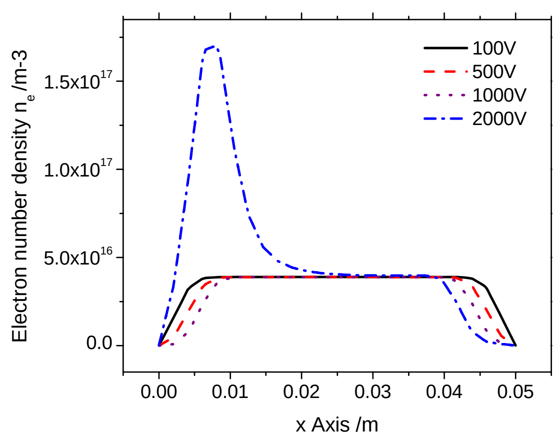

Figure 3. The electron number density vs radio-frequency applied voltages. The parameters are: the position is y=5cm; RF frequency is f=13.56MHz; gas pressure is p=0.4torr; gas specie is O_2.

From Figure.4 and Figure.5, the studies in different radio-frequency frequencies show that, with the radio-frequency frequencies increasing, the peak electron density closes to a constant, but the thicknesses of sheaths near the electrodes get thinner. It can be explained that with the increase of radio-frequency frequencies, the energy transfer between electrostatic field and plasma electrons is enhanced.

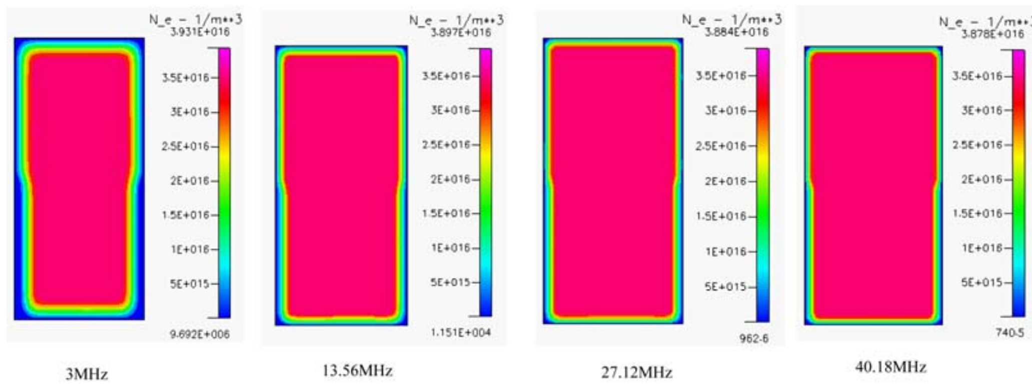

Figure4. The influence of varying radio-frequency frequencies on the electron number density in chamber

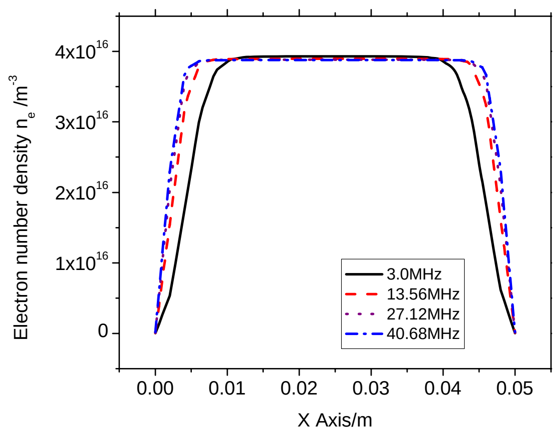

Figure 5. The electron number density vs radio-frequency frequencies. The parameters are: the position is *y*=5cm; RF applied voltages is V_{RF}=100V; gas pressure is *p*=0.4torr; gas specie is O_2.

The studies in different gas pressures can be recognized in Figure. 6 and Figure. 7. It can be seen that the electron number density increases with increasing pressures, but the electron temperature decrease. An explanation is that when the gas pressure is lower, the mean free path of plasma is smaller. Frequent collision between electrons and heavy particles will occur. More and more electron will be generated. The energy of electron can be transferred to heavy particles more quickly. Consequently, the electron energy and electron temperature will decrease.

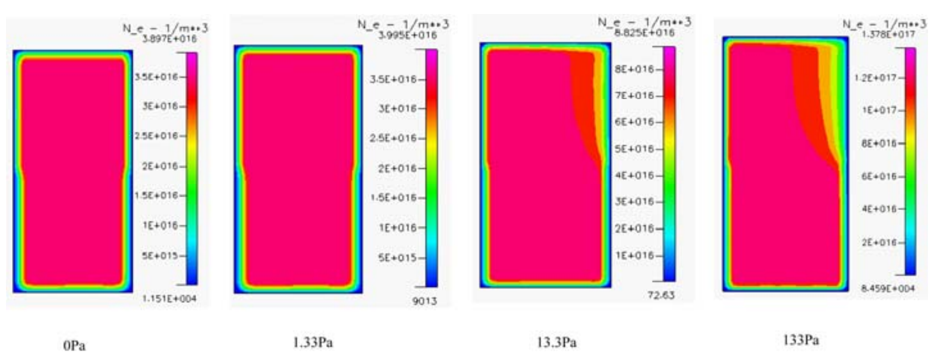

Figure 6. The influence of varying gas pressures on the electron number density in chamber

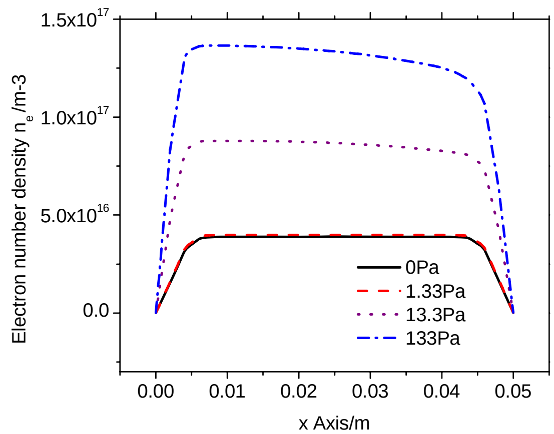

Figure 7. The electron number density vs gas pressures. The parameters are: the position is y=5cm; RF applied voltages is V_{RF}=100V; RF frequency is f=13.56MHz; gas specie is O_2.

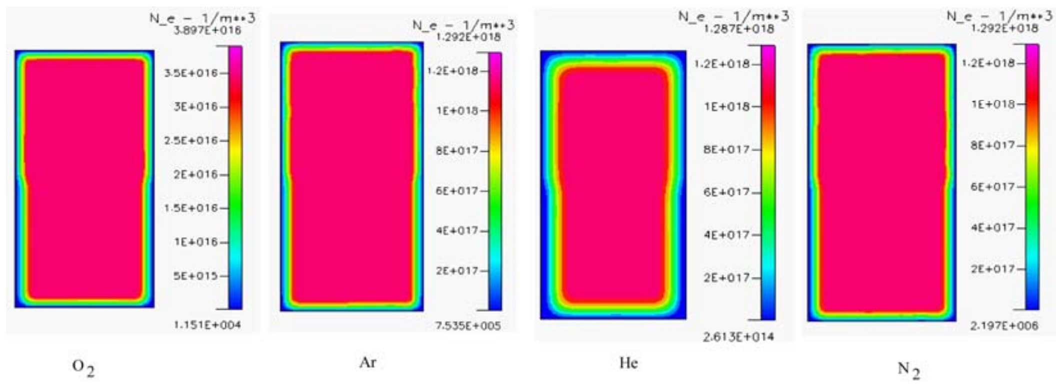

Figure 8. The influence of varying gas species on the electron number density in chamber

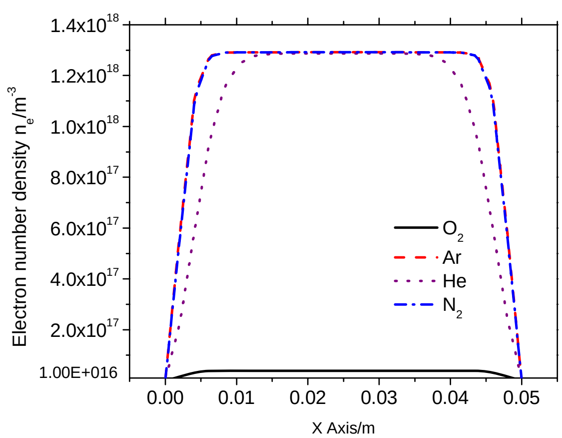

Figure 9. The electron number density vs gas species. The parameters are: the position is y=5cm; RF applied voltages is V_{RF}=100V; RF frequency is f=13.56MHz; gas pressure is p=0.4torr.

The studies on the effect of gas species were given in Figure 8 and Figure 9. The results show that the electron density in O_2 discharge is the lowest and lower than the others 2 orders times. The density profile of Ar discharge is similar to that of N_2 discharge. The plasma sheath in N_2 discharge has a maximal thickness. It can be concluded that the gas specie and pressure play a key role in gas discharge.

In Figure. 10, the dual-band power-driven discharge for CCP is calculated. It can be seen that dual-band power-driven CCP is more efficient at higher plasma density. But it has a poor homogenous in discharge chamber.

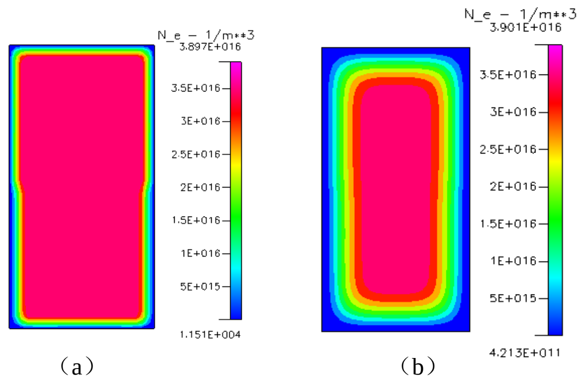

Figure 10. The density profiles comparison between (a)the single- band power-driven and (b) dual-band power-driven. The parameters are: RF applied voltage is V_{RF}=100V; RF frequency is f=13.56MHz; gas pressure is p=0.4torr; gas specie is O_2.

3. CONCLUSION

This paper uses the time-dependent fluid model to compute the characteristics of capacitive coupled plasma. From the results obtained, the electron number density presents a minimum near the electrodes, and presents a maximum between the positive and the negative electrodes. The distinguishing feature of CCP is the presence of oscillating sheaths near electrodes where displacement current dominates conduction current. The studies on the dependences of RF applied voltages (V_{RF}=100-2000V), RF frequencies (f=3.0-40.68MHz), pressures (p=0.001-1torr), and gas species show that, it is possible to reach a peak density by well choosing the charge parameters. These informations will help us to analyze the characters of CCP for application.

Acknowledgments

This work is supported by the National Natural Science Foundation of China under Grant 51107033.

REFERENCES

[1] G. J. M. Hagelaar and L. C. Pitchford, "Solving the Boltzmann equation to obtain electron transport coefficients and rate coefficients for fluid models," Plasma Sources Science and Technology, 14, 722-726 (2005).
[2] M. Hayashi and T. Nimura, "Calculation of electron swarm parameters in fluorine," Journal of Applied Physics, 54, 4879-4882 (1983).
[3] F. Bouanaka, S. Rebia, H. Bahouh, and S. Sahli, "Numerical Modeling Of Electron's Trajectories In Cold Plasma By PIC Method," Moroccan Journal of Condensed Matter, 12, 263-266 (2011)
[4] L. Marques, J. Jolly, and L. L. Alves, "Capacitively coupled radio-frequency hydrogen discharges: The role of kinetics," Journal of Applied Physics, 102, 063305-14 (2007).
[5] A. Salabas, G. Gousset, and L. L. Alves, "Two-dimensional fluid modelling of charged particle transport in radio-frequency capacitively coupled discharges," Plasma Sources Science and Technology, 11, 448-465 (2002).
[6] A. Salabas, L. Marques, J. Jolly, G. Gousset, and L. L. Alves, "Systematic characterization of low-pressure capacitively coupled hydrogen discharges," Journal of Applied Physics, 95, 4605-4620 (2004).
[7] A. Bouchikhi, "Two-Dimensional Numerical Simulation of the DC Glow Discharge in the Normal Mode and with Einstein's Relation of Electron Diffusivity," Plasma Science and Technology, 14, 965-973 (2012).

[8] W. He, X. Liu, R. Xian, S. Chen, R. Liao, F. Yang, et al., "Kinetics Characteristics and Bremsstrahlung of Argon DC Discharge Under Atmospheric Pressure," Plasma Science and Technology, 15, 335-342 (2013).
[9] P. L. G. Ventzek, R. J. Hoekstra, and M. J. Kushner, "Two-dimensional modeling of high plasma density inductively coupled sources for materials processing," Journal of Vacuum Science Technology B, 12,461-465 (1994)
[10] T. J. Sommerer, M. J. Kushner , "Numerical investigation of the kinetics and chemistry of rf glow discharge plasmas sustained in He, N_2, O_2, $He/N_2/O_2$, $He/CF_4/O_2$, and SiH_4/NH_3 using a Monte Carlo-fluid hybrid model," Journal of Applied Physics, 71, 1654-1660 (1992)
[11] P. L. G. Ventzek, M. Grapperhaus, and M. J. Kushner, "Investigation of electron source and ion flux uniform ity in high plasma density inductively coupled etching tools using two-dimensional modeling," Journal of Vacuum Science Technology B, 12, 3118-3122 (1994)