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Electrical characteristics for capacitively coupled radio frequency discharges of helium and neon

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Abstract. In this study, a symmetric radio frequency (RF) (13.56 MHz) electrode discharge system of simple geometry has been designed and made. The electrical properties of capacitive RF discharge of pure neon and pure helium have been obtained from current and voltage waveforms using different reactor designs. Calculations are done, in detail, according to the homogeneous discharge model of capacitively coupled RF. Electrical properties of bulk plasma and sheath capacitance are also investigated at low pressure using this model.

Keywords. Discharge in vacuum; electric and magnetic measurements; plasma properties; high frequency and RF discharge; homogeneous discharge model of CCRF.

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1. Introduction

It is interesting to study the behaviour of plasma. There are many ways to obtain gas discharge and one of them is the capacitively coupled radio frequency (CCRF) discharge, which is used in this work. CCRF discharge is formed between the two electrodes placed symmetrically parallel. Here, the RF voltage is usually applied to one of the two electrodes and the other electrode is used for grounding. The plasma sheath and bulk plasma are very important for CCRF discharge. They are formed with the RF power. The net positive charge in the sheath is equal to the negative charge on the electrode. A neutral plasma forms an environment which is free of charged particles moving in random directions [1,2].

CCRF method is used to form plasma and a model was selected to calculate some parameters and to observe electrical properties of this type of discharge. CCRF method was based on a work by Godyak and collaborators who have developed a model using the sheath and bulk plasma having homogeneous densities [2]. Godyak *et al* also investigated CCRF discharge for argon (Ar) in 1991 [3]. The homogeneous discharge model of CCRF is used in this experiment. In homogeneous model, the calculations can be used with values of current and voltage. The bulk plasma has an electron temperature T_e and an ion density n_i which is equal to electron density n_e because of quasineutrality. The first two noble gases have been selected for the experiments. This study examines and compares the electrical characteristics and sheath capacitance changes with RF power and pressure for He and Ne discharges. Another aim of the study is to obtain differences between the current and voltage values of the Ne and He discharges.

The organization of this paper is as follows: After the Introduction, in §2 the experimental set-up is explained and then the model is described in §3. Graphs and results are drawn with data in §4. By introducing the results of analysis with an oscilloscope, the novelty and importance of this study are emphasized in Conclusion.

2. Experimental set-up

In this system, a reactor made of quartz glass was used to form plasma with the CCRF discharge and the power was supplied by Cesar 136 Auser Ethernet RF-Generator Navio Matching Network used for stable current and voltage values. This device has been designed for symmetric RF discharge. It enables easier measurement of the voltage and current. The electrodes were parallel to each other with cylindrical symmetry, the distance between them being 22 cm. The thickness of the electrode was 4.5 cm and the radius was 5 cm. One of the electrodes was connected to the positive pole and the other one was grounded. The current

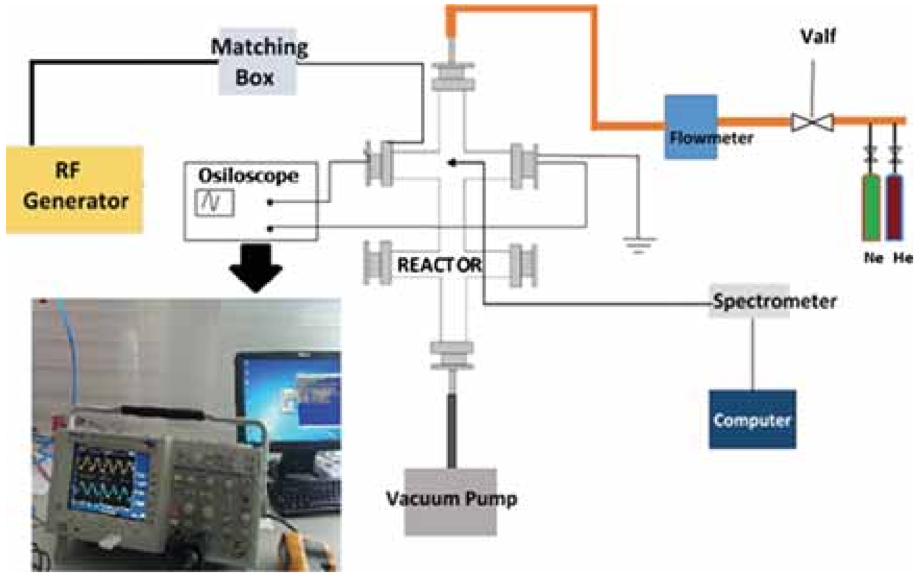


Figure 1. Schematic diagram of the experimental set-up of the capacitive discharge system.

and voltage of the plasma were measured with Tektronix P5100A voltage and Tektronix 6021A current probes connected via Tektronix 3052C oscilloscope. Plasma reactor was connected to Edwards' mechanical pump and the vacuum gauge controller (figure 1). The discharge system was kept constant. A vacuum pump provided low pressure. The electrical characteristics for different pressures were observed in terms of how they change. The current and voltage for two gases at different pressures were recorded at every 5 min for 30 min. The root mean square (RMS) voltages and currents were obtained from the oscilloscope. Accordingly, the graphics are drawn and the individual electrical properties for both Ne and He are analysed. Next, the results for the two plasmas have been compared with each other under similar circumstances.

3. Modelling and equations for this type of discharge

Homogeneous discharge model of CCRF is selected for calculating current and voltage in this study. Equivalent circuit is shown in figure 2. The sheath capacitor (C_s), the bulk plasma resistor (R_{bp}) and the bulk plasma inductor (L_{bp}) occur in the bulk plasma circuit. The parameters such as the electron plasma frequency (w_{pe}) and the capacitance of the symmetric parallel electrodes (C_e) are used to calculate the inductance L_{bp} using the following equations [2,4,5]:

$$w_{pe}^2 = \frac{ne^2}{\epsilon_0 m} \tag{1}$$

and

$$L_{bp} = \frac{1}{w_{pe}^2 C_e} = \frac{md}{A n_e e^2} \tag{2}$$

where e is the charge of electron and ϵ_0 is the permittivity constant. A, n_e, m and d represent the surface area of the parallel plate, the electron density, the mass of the electron and gap between the electrodes, respectively. For this experiment, homogeneous discharge model of CCRF should be used at low pressure but the model can also be used at atmospheric pressure. This model has to be modified to use under low pressure. The bulk plasma inductance and sheath capacitance cause a resonance effect. The resonance improves the heating mechanism [6,7]. Nonlinear plasma series resonance (PSR) effect is also present while this discharge is used. Because of the PSR effect of the homogeneous discharge model of CCRF, the expected current is lower than RMS current [8,9].

The electron neutral collision frequency may be obtained using the following equation:

$$\nu = n_e d_{col}^2 \sqrt{\left(\frac{8\pi k_B T_e}{m}\right)}, \tag{3}$$

where n_e is the population density of the electrons and d_{col} is the cross-section of the electron neutral collision [4]. Boltzmann constant k_B and electron temperature T_e [10] can be used to compute the electron neutral collision frequency. The resistance of the bulk plasma is defined as

$$R_{bp} = \frac{\nu L_{bp}}{c_f}, \tag{4}$$

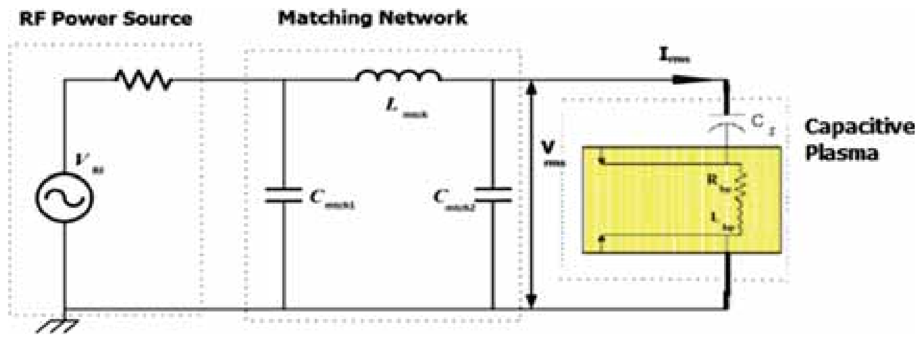


Figure 2. Equivalent circuit for the capacitively coupled RF discharge of the homogenous model.

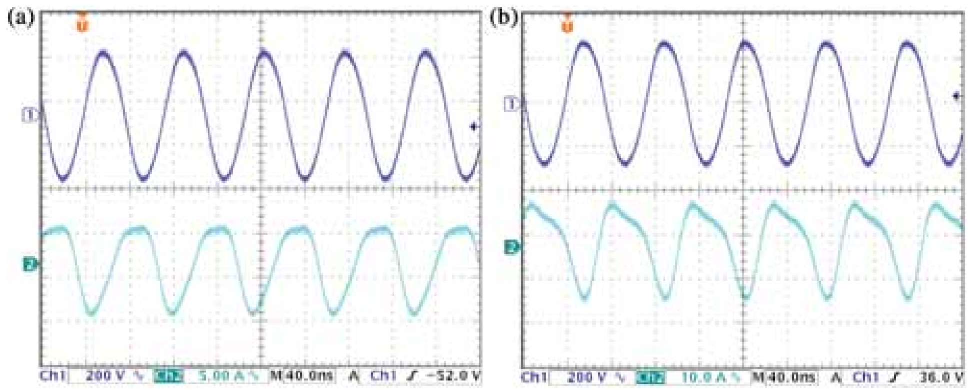


Figure 3. Snapshots of oscilloscope display for (**a**) He and (**b**) Ne discharges.

where c_f is the correction factor. c_f is not used for the discharge at atmospheric pressure. PSR effect, the change of the electric field and electron drift velocity are related with the correction factor mentioned.

Li *et al* [5] have used the following equation for capacitively coupled plasma at atmospheric pressure:

$$R_{bp} = \nu L_{bp}. \tag{5}$$

For homogeneous discharge model, the sheath capacitance C_s can be calculated using the following equation:

$$C_s = \frac{I_{rms}}{w V_{RMS}}, \tag{6}$$

where w is the frequency of RF supply produced with 2π. The dissipated power of plasma may be calculated using V_{RMS} (RMS potential), I_{RMS} (RMS current) and φ (phase difference) using the following equation:

$$P = I_{RMS} V_{RMS} \cos \varphi. \tag{7}$$

4. Results and discussion

The values of voltage and current have been recorded from oscilloscope using the waveform graphs for all measurements. The examples of waveform snapshots are shown in figure 3. Data obtained from the experiment can be used to draw graphs of electrical properties for pure He and pure Ne plasmas. The voltage and current characteristics of the He and Ne discharges due to the RF power are presented in figures 4 and 5. RMS voltage and current increase with the rise of power as expected. It is pointed out that He discharge has lower RMS voltage than Ne discharge till 200 W RF power. For 200 W power, RMS voltage of He discharge is a little bigger than Ne discharge at 540 mTorr pressure (figure 4). As seen from the current characteristics, RMS current of Ne discharge is always greater than He discharge (figure 5).

When RF power is applied to the gases, the atoms of the gas gain energy from the RF electric field. When He gas and Ne gas at 0.05 l/min flow rate are used to generate Ne and He discharges, the pressures of He and Ne discharges are obtained as 540 mTorr and 900 mTorr in the capacitive coupled reactor, respectively. Therefore, Ne discharge causes more pressure with respect to

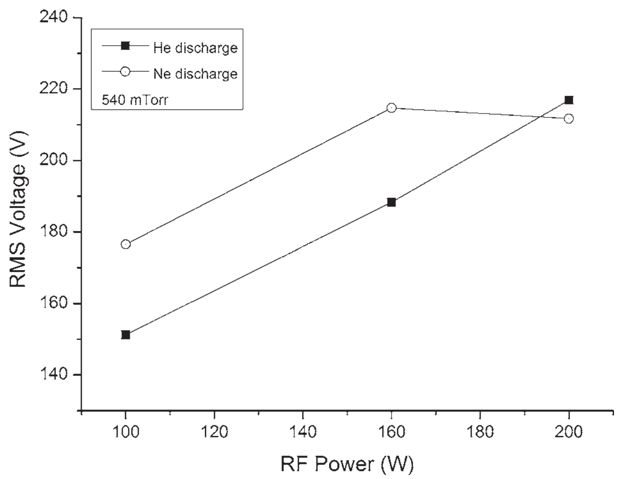


Figure 4. The change of RMS voltage for Ne and He discharges at 540 mTorr pressure.

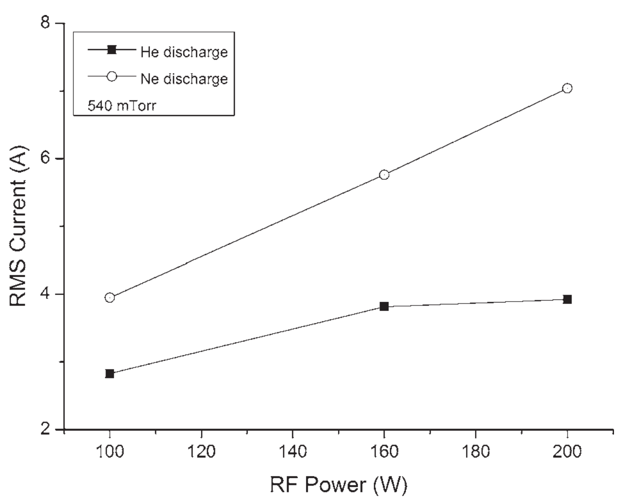


Figure 5. The change of RMS current for Ne and He discharges at 540 mTorr pressure.

He discharge at the same volume flow rate. It has been shown that there is a good agreement with the universal gas law.

In figures 6 and 7, it can be seen that He discharge still has lower RMS voltage and RMS current values with respect to Ne discharge for the same volume flow rate.

Ne discharge produces 187.1 V at 100 W, 211.2 V at 160 W and 221.5 V at 200 W, then He discharge produces 151.7 V at 100 W, 191.3 V at 160 W and 216.9 V at 200 W RMS voltages at the same volume flow rate in figure 6. In addition to this, figure 7 shows 3.764 A at 100 W, 5.815 A at 160 W and 6.608 A at 200 W RMS currents for Ne discharge and 2.828 A, 3.857 A and 3.924 A RMS currents for He discharge at the same RF powers.

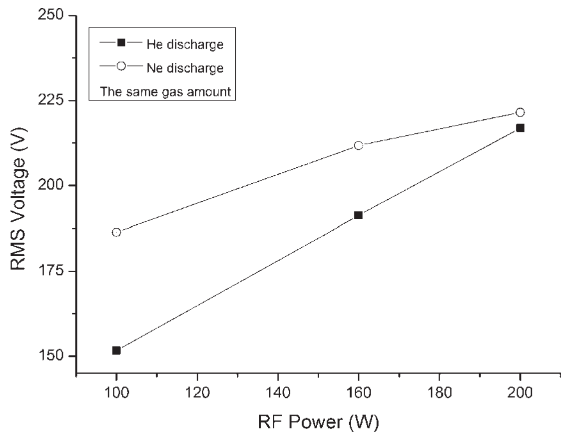
In this case, it is seen that when RF power is applied to He and Ne gases at the same volume flow rate (0.050 l/min), the pressures were obtained as 540 mTorr and 300 mTorr for He and Ne, respectively. We expected the same vacuum pressure to be added to each gas in the system. Different pressures affect the voltage and current characteristics of discharges. The voltage and current decrease with the increase of pressure and this experiment verifies this. The differences between the discharge and pressure are represented in figures 8 and 9. Ne discharge already has bigger voltage than He discharge, however, the pressure affects Ne discharge more than He discharge.

The RF power of 160 W was selected for the pressure–RMS voltage and the pressure–RMS current graphs. Due to the different volume flow rate, when the pressure increases, RMS voltage and current decrease.

At low pressure, collisions between particles are reduced. Hence, the drift velocity of the electrons is affected by the applied electric field. Since this affects plasma density, V_{RMS} and I_{RMS} become connected with pressure.

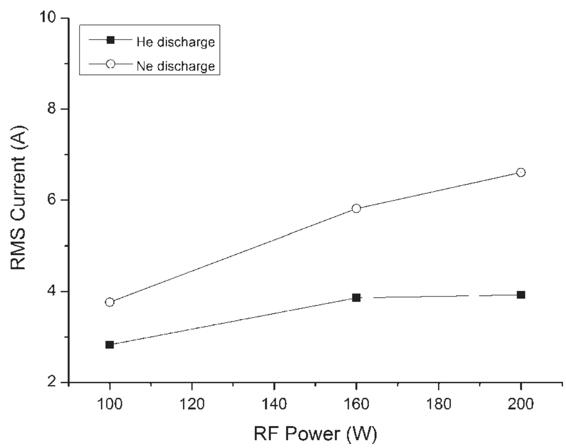
The sheath capacitance is related to RMS current and RMS current is related to the RF power. The sheath capacitances of Ne and He discharges with respect to RF power are presented in figure 10 (as predicted by eq. (6)).

It is known that the sheath capacitance is inversely proportional to the sheath resistance [11–13]. Sobolewski [12] reported that the sheath impedance is inversely proportional to the sheath capacitance. Hence, sheath impedance of Ne discharge is lower than that of He discharge and the low sheath impedance has some advantages for the high-frequency plasma deposition. Therefore, Ne discharge may be used for better and efficient deposition rather than He discharge. The sheath capacitances are calculated for RF powers as 100 W, 160 W and 200 W RF powers and the pressure as 540 mTorr, 750 mTorr and 900 mTorr. Sheath capacitance also was calculated for different pressures vs. RF power. The graphs are drawn using these values and all values are seen in table 1. Sheath capacitances are computed using eq. (6). In this context, two different graphs were obtained. The RMS current and voltage of Ne discharge are increased proportionally with each other by increasing RF power. In this case, the sheath capacitance of Ne discharge increases with increase in RF power. However, this situation is quite different for He discharge because of the RMS current and voltages. RMS voltage increases with higher rate due to RMS current values and this causes disproportional values of sheath capacitance. Rarely, the sheath capacitance of He discharge decreases with increasing RF power unlike the sheath capacitance of Ne discharge. It can be said that pressure is proportional to the sheath capacitance in general.



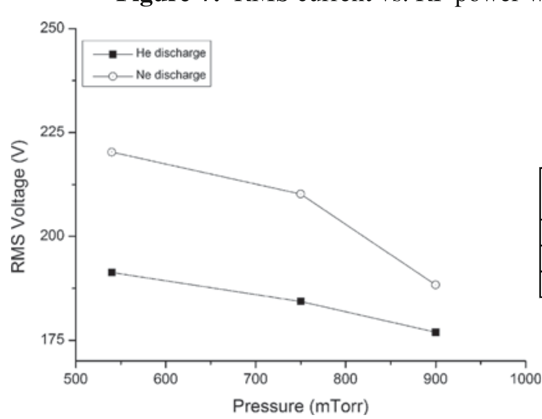
Power (W)	RMS Voltage (V)	
	Helium discharge	Neon discharge
100	151.7	187.1
160	191.3	211.2
200	216.9	221.5

Figure 6. RMS voltage vs. RF power with the same volume flow rate.



Power (W)	RMS Current (A)	
	Helium discharge	Neon discharge
100	2.828	3.764
160	3.857	5.815
200	3.924	6.608

Figure 7. RMS current vs. RF power with the same volume flow rate.



Pressure (mTorr)	RMS Voltage (V)	
	Helium discharge	Neon discharge
540	191.3	220.3
750	184.3	210.2
900	176.9	188.3

Figure 8. The change of RMS voltage for Ne and He discharges vs. pressure.

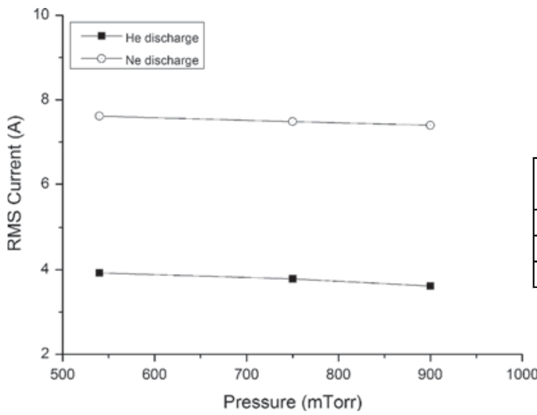
In this study, the current and voltage values for both cases were also analysed (figure 11). It is obvious that the change of time remains stable for both discharges of Ne and He for the same pressure.

The plasma resistance can be given by the following equation [14]:

$$R_\mathrm{p} = \frac{\text{Input power value}}{i_{\mathrm{RMS}}^2}. \tag{8}$$

Accordingly, it is seen from the calculations made here that the plasma resistance is inversely proportional to the RF power (figure 12).

Figure 13 represents typical $V_{\mathrm{RMS}}/I_{\mathrm{RMS}}$ plots of He and Ne discharges at different powers. This gives an idea about the operating regime of the abnormal glow. As seen from the current and voltage values at 200 W, the electrodes become sufficiently hot and electrons are emitted by the cathode thermionically. Also,



Pressure (mTorr)	RMS Current (A)	
	Helium discharge	Neon discharge
540	3.924	7.616
750	3.784	7.486
900	3.615	7.399

Figure 9. The change of RMS current for Ne and He discharges vs. pressure.

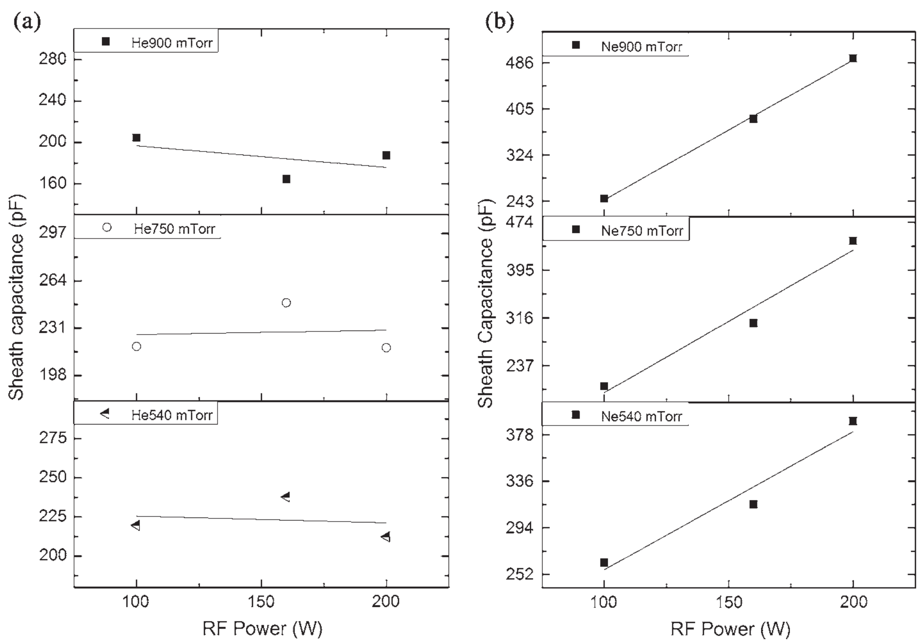


Figure 10. Sheath capacitance vs. RF power for all experiment pressures for (**a**) He and (**b**) Ne discharge.

Table 1. Sheath capacitance values for Ne and He discharges vs. power and pressure.

		Sheath capacitance (pF)	
Pressure (mTorr)	RF Power (W)	Neon discharge	Helium discharge
540	100	262.610	219.530
	160	314.940	237.670
	200	390.260	212.340
750	100	202.679	218.198
	160	307.573	248.684
	200	443.645	217.309
900	100	247.249	204.696
	160	387.225	164.531
	200	493.862	187.633

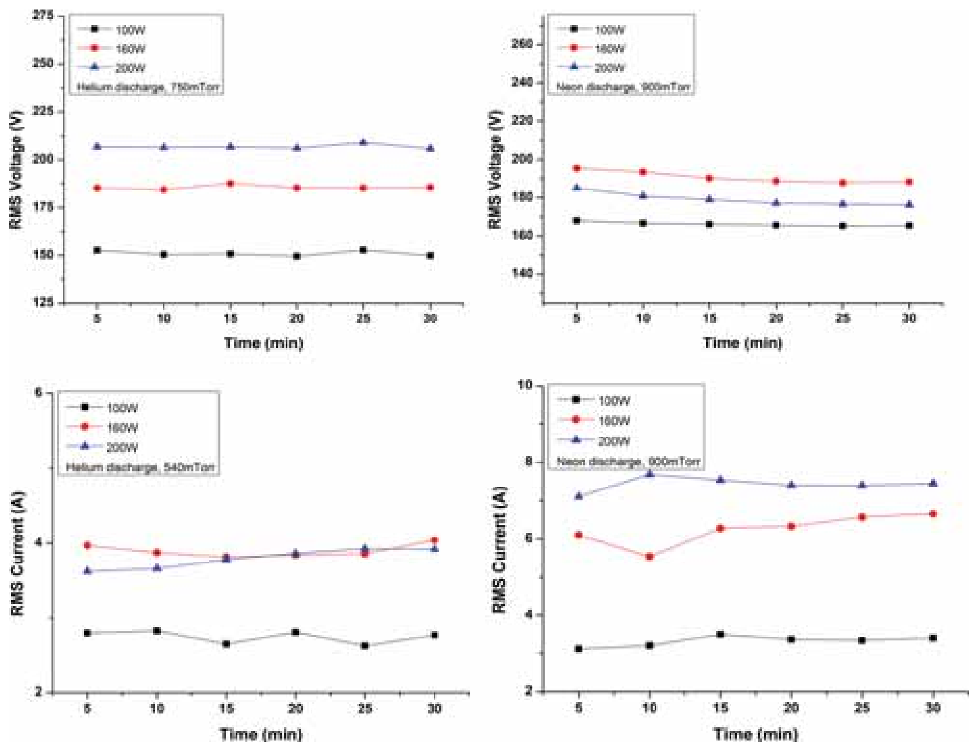


Figure 11. RMS currents and voltages vs. time for He and Ne at different powers and pressures.

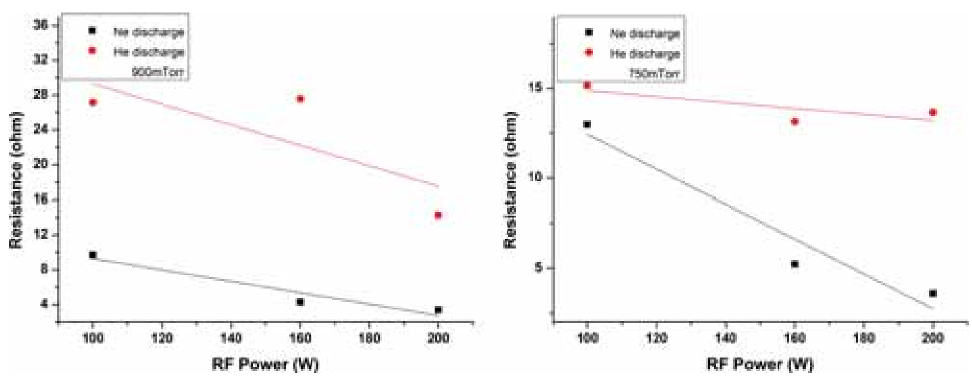


Figure 12. Plasma resistances vs. RF powers under different pressures.

it may be said that $V_{\mathrm{RMS}}/I_{\mathrm{RMS}}$ values for the previous state from the applied RF power as 100 W show that the discharge may make a transition back to Townsend regime.

5. Conclusion

Modified homogeneous discharge model of CCRF was used for discharge at low pressure and calculations were done using the experimental results. It is seen that homogeneous discharge model of CCRF could be used at low pressure with modification. The electrical properties of He and Ne discharges were also investigated and presented with a comparison.

Voltage and current values of He discharge are smaller than that of Ne. Therefore, it may be said that Ne discharge is a better conductor than He discharge. Sheath capacitance of Ne discharge is larger than that of He discharge. Thus it may be said that the sheath resistance of Ne is lower than He. The sheath capacitance decreases with the increase of RF power, thus the sheath impedance also increases with the rise of RF power. However, the sheath capacitance of He discharge is almost stable despite the increase of RF power. As the electron temperature is inversely proportional to the

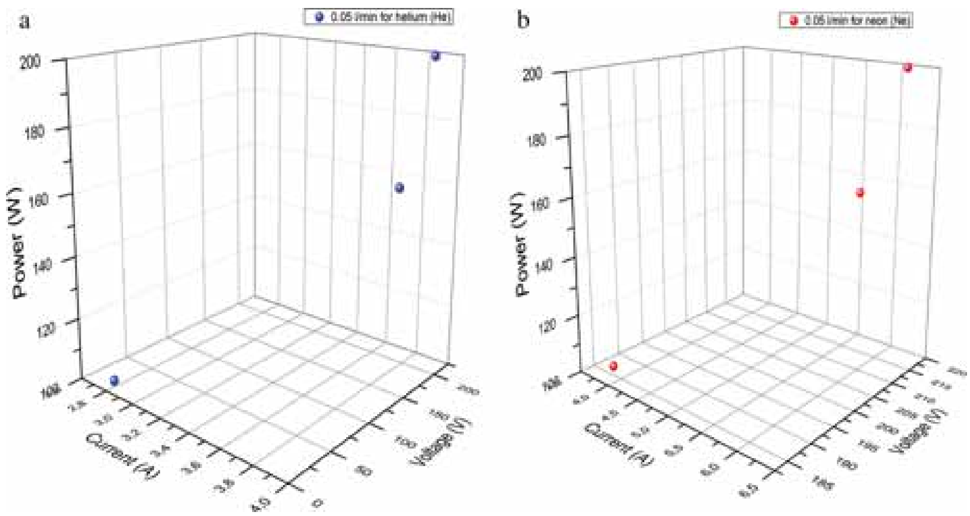


Figure 13. A typical $V_{\mathrm{RMS}}/I_{\mathrm{RMS}}$ plot of (**a**) He and (**b**) Ne discharges for different powers (100, 160 and 200 W).

electron density, it may be understood that the electron density of Ne discharge increases more than that of He.

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