ISSN 2347-3487

DISCHARGE CHARACTERISTICS OF GLIDING ARC PLASMA REACTOR WITH ARGON/NITROGEN

A. EL-Zein[1], G. El-Aragi[2], M. Talaat[3], and A. El-Amawy[4]
[1]Electrical Power and Machines Department, Faculty of Engineering, Zagazig University, Zagazig, Egypt
prof.elzein@yahoo.com
[2]Plasma Physics and Nuclear Fusion Department, N. R. C., EAEA, Cairo, Egypt
elaragi@gmail.com
[3]Electrical Power and Machines Department, Faculty of Engineering, Zagazig University, Zagazig, Egypt
m_mtalaat@eng.zu.edu.eg
[4]Plasma Physics and Nuclear Fusion Department, N. R. C., EAEA, Cairo, Egypt
eng.amira85@yahoo.com

ABSTRACT

Gliding arc discharge plasma has properties of both thermal and non-thermal plasma conditions. Gliding arc discharge plasma in the atmospheric pressure with argon/nitrogen and its characteristics are described. Some experimental results about alternating current gliding arc plasma generator have been obtained. It seems that the current density strongly depends on the gas, and increased with increasing discharge current and gas flow rate. Also, the discharge current of gliding arc discharge plasma in nitrogengas is greater than one in argon gas because of nitrogen gas need to higher breakdown voltage than argon gas. The intensity of gliding arc discharge plasma increased with increasing the gas flow rate. In addition to the oscillograms of discharge current in each case of argon andnitrogen were obtained. Electron temperatures of argon and nitrogen plasma were calculated to be $22800^o\ K$, $8400^o\ K$ respectively. The characteristics of both argon andnitrogen gases in atmospheric pressure were investigated like current density, electron density with flow rates (5, 10, 20, and 40) Standard Cubic Foot per Hour ($SCFH$). All the experimental results were tabulated.

Indexing terms/Keywords

Gliding arc discharge (GAD) plasma; discharge at the atmospheric pressure; Ar and N_2 gases; gas flow rate; diagnostic technique

INTRODUCTION

The Gliding arc discharge device is a simple and inexpensive way to generate non-thermal plasma. It has a dual character of thermal and non-thermal plasma, and can involve relatively high electric power compared with the corona discharge. They are highly reactive and often have a high selectivity for chemical processes [1].

The Gliding arc discharge is usually generated between two diverging electrodes typical ina gas flow [1]. The discharge ignites at the shortest distance between the electrodes (1 mm). Typical breakdown voltages are (2-6) kV [2]. The formation of hot quasi-thermal plasma corresponds with a decrease in voltage and strong increase in current [2]. Owing to the gas flow, the discharge moves downward and the length of the plasma column increases. This increasing length causes an increase of the heat losses in the column, which exceeds the input energy of the power supply [2]. The quasi-thermal plasma converts into non-thermal plasma corresponds the decrease in current and the increase in voltage due to the increasing resistivity of the plasma. Eventually, the plasma extinguishes as the power supply cannot maintain such a long plasma column. At this point the recombination of the plasma starts and a re-ignition of the discharge occur at the minimum distance between the electrodes [2]. This causes the self-pulsing nature of the gliding arc discharges, which is always clearly visible in current–voltage waveforms and typically occurs on 10 ms timescales [2, 3].

Gliding arc Discharge (GAD) is a new technology of non-thermal plasma. In recent years, a number of researchers are interested in this new technology for environmental protection.

GAD has been studied for combustion, gas cleaning, and production of syngas [4], and water treatment [5, 6]. GAD can also be magnetically stabilized [7].

GAD plasma efficiently destructed volatile organic compounds (VOCs) (higher than 90%), NO*x*, So*x* [8]. The phenol in solution can be degraded by gas-liquid gliding arc discharge [2-9].This kind of source of high energy electrons without heating the plasma gas in the whole volume of plasmareactor chamber is essential for typical plasma chemistry applications.

In this paper, the source of GAD experiment was AC power supply (6.6 kV) with frequency 50 Hz. The gases which used in the experiment were Argon (Ar) and Nitrogen (N_2). The discharge characteristics of each gas like its discharge voltage, discharge current, current density, electron temperature and electron density were investigated.

The characteristics of discharge current with different gas flow rate of Ar and N_2 were studied and illustrated in graph.
The equations of the ionization process in Ar and N_2 were clarified.
The photographs of each gas were illustrated at different flow rates (5, 10, 20, 40) SCFH to follow the GAD plasma streamer.
The mathematical equations for calculating current density, electron temperature and electron density were obtained. Some curves were drowning like electron density varies with flow rate of gas.

Experimental Setup

GAD experiment consists of two identical diverging electrodes made of copper each with length (44mm), width (26mm), thickness (15mm), arc (deviation of electrode)angle (120º) and the gap between two electrodes (1 mm).

The electrodes are connected to AC power supply (6.6kV) via resistor (R=200kΩ) to avoid high current. The input voltage was controlled by using variac (slidacs).

The AC power supply is step-up transformer with ratio (1:30). The gas was injected from narrow tube located from narrow gap between two electrodes.

The two electrodes and the gas pipe were located inside glass bottle, see Fig. 1.

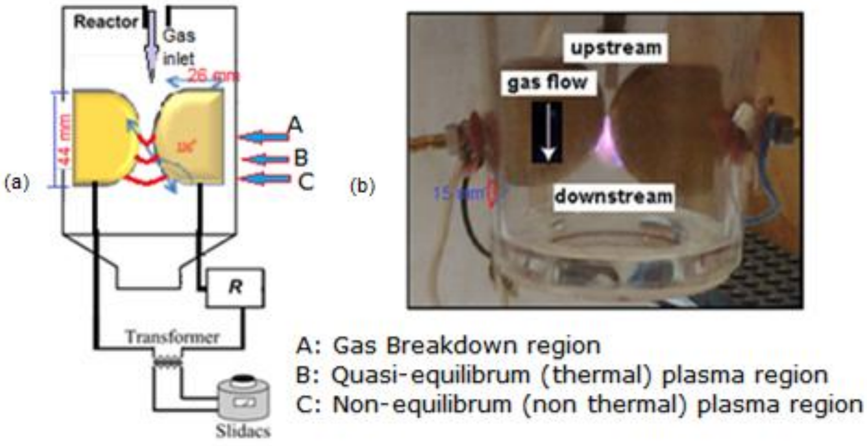

Fig. 1(a) Schematic of gliding arc and the electric scheme, (b) GAD plasma photo

Figure1 represented the schematic diagram of experimental setup with indication of plasma stages.

In A, as shown in fig1, was the region of Gas Breakdown.

In B, was the region of quasi-equilibrium (thermal) plasma.

In C, was the region of non-equilibrium (non-thermal) plasma.

The gases used for the experiment were Ar and N_2 wheregas flow rate was controlled from 5 SCFH to 50 SCFH by the pressure regulator. Discharge voltage was controlled by the voltage slide regulator and increased by using the high voltage transformer (1:30), and then high voltage was applied to the electrodes. Therefore, the frequency of electric discharge is 50 Hz. Discharge current was measured using both of clamp digital meter (for digital value) and rogowiski coil to connect to oscilloscope (for following the current oscilligram).

Methods of Analysis

1. Electric field(E)

$E = V/d$ (1)

(Reduced electric field = breakdown voltage /gap distance)

So, E is estimated to be (2.7 kV/mm) for Ar gas and (3.3 kV/mm) for N_2 gas at gap distance =1mm where V_{br} (Ar) =2.7 kV, V_{br} (N_2) = 3.3kV.

2. Dissociation and Ionization

The molecules constitute of elements under ionic, covalent, metallic and van der Waals bonds for inert gases. These bonds may be single, double or tripple one. Dissociation is a process required to rupture the combining bonds between atoms forming the molecules.

Dissociation energy required increases from single to double to tripple bond, with a weak value for van der Waals type for inert gases.

In the present paper, N_2 gas moleculehas a tripple bond type and needs of 9.8 eV for dissociation [12]. But Ar gas needs small dissociation energy compared to N_2 because its bonds are the weak van der Waals type [13].

For ionization energy required for N_2 and Ar are nearest from each other with values of 14.54 and 15.76 eV for the two gases respectively [13]. The above results are shown in table 1.

In nitrogen, [14],

$N_2 \rightleftarrows 2N$ (9.764 eV) dissociation energy

$N \rightleftarrows N^+ + e$ (14.54 eV) ionization energy

$N^+ \rightleftarrows N^{++} + e$ (29.6 eV) ionization energy

In Argon, [15],

$Ar \rightleftarrows Ar^+ + e$ (15.76 eV) ionization energy (neglecting dissociation energy due to its small van der Waals value)

$Ar^+ \rightleftarrows Ar^{++} + e$ (27.64 eV) ionization energy

where: (1eV = 11600 $\mathring{K}$)

3. Electron temperature(T_e)

Nitrogen at 8000 K has an enthalpy five times higher than argon [14], since the energy gained by the one-atom gases in the plasma column is given by the specific heat and ionization energy, while in two-atom gases, in addition, the great volume of energy is obtained from the dissociation of molecules into atoms.

Electron temperature can be roughly calculated usingEinstein's equation of electrons in argon and nitrogen [16].

Using the following equations

$k_BT_e/e = D_e/\mu_e$ (a)

$N = 3.3 \times 10^{16}P$ (b) (2)

$D_e = K.10^5/P$ (c)

where k_B, e, μ_e, and D_e are Boltzmann constant, electron charge, electron mobility, electron diffusion constant (expressed as a function of E/N) respectively.

Also N, P is Neutral gas density and atmospheric pressure respectively ($E/N = 1.1 \times 10^{-15}$ V.cm^2 for (Ar), $E/N = 1.3 \times 10^{-15}$ V.cm^2 for (N_2)). Also k is the electron diffusion constant (2.9for (N_2) and 6.3for (Ar)).

From the previous data

D_e= 828 cm^2/s (for Ar), D_e= 381 cm^2/s (for N_2)

and μ_e = 434cm^2/ V.S and D_e/μ_e = 1.9 eV for (Ar)

Also, μ_e (for N_2) =552cm^2/ V.S, D_e/μ_e = 0.7 eV for (N_2)

So,

$T_e = e/K_B.\ D_e/\mu_e = 22800\ \mathring{K}$ = 1.9 eV for (Ar),

$T_e = e/\ K_B.\ D_e/\mu_e = 8400\ \mathring{K}$ = 0.7 eV for (N_2).

Which means that 1 eV equivalent to =11600 $\mathring{K}$

4. Current density(J)

The current density (J) was obtained from dividing the discharge current (I) by the area of plasma (S).

$J = I / S$ (3)

The cross section area which the current crosses is a rectangle shape of length equal to the thickness of electrodes 15 mm with side drop starting from the minimum distance of electrodes downward which differs from the used gas to another.

In the present experiment, the side length equal 10 mm and 12 mm and area of 1.5 cm^2 and 1.8 cm^2 for (Ar) and (N_2) respectively.

The previous results are collected and given in table 2.

Table 1 molecules bond type and related dissociation and ionization energies

Gas	Bond type	Dissociation energy(eV)	Ionization energy(eV)
N_2	Triple	9.8	14.54
Ar	Van der waals	Weak values	15.76

Table 2 constants relating Einstein's equation and other gas constants

(kB = 1.38 x 10-23 J/k ,e = 1.6 x 10-19 C ,P = 760 torr)

Gas	E/N v.cm^2	D_e cm^2/s	μ_e cm^2/v.s	D_e/μ_e eV	T_e k°
N_2	1.3×10^{-15}	381	552	0.7	8400
Ar	1.1×10^{-15}	828	434	1.9	22800

At flow rate 5 SCFH, J = 20 A/cm^2, J = 27.8 A/cm^2 for (Ar) and (N_2) respectively, with S = 1.5 cm^2, S = 1.8 cm^{2}for (Ar) and (N_2) respectively.

5. Electron density(n_e)

The averaged electron density(n_e) can be calculated from the following equation, [11],

$n_e = J/ (e\ E\ \mu_e)$(4)

The above equation can be rewritten as follows

$n_e = J / (\mu_e p \times (E/P) \times e)$ (5)

Accordingly n_e at 10 SCFH equal to 4.4×10^{13} cm^{-3}, 2.6×10^{13} cm^{-3} for (Ar) and (N_2) respectively.

The nitrogen has an electronegative characteristics gas, therefore the electron density number becomes smaller and decreasing electron density leads to increasing resistivity, see table 3 for a comparison between (Ar) and (N_2) gases.

Results and discussions

The current flowing through the gas was measured by using clamp meter and Rogowiski coil. The discharge current increased with increasing gas flow rate as shown in fig. 2. This may be due to promotion of gas ionization by the gas flow rate increasing. In this experiment, high electric power was supplied to the 1 mm gap electrode. In Argon gas the ionization is promoted with increasing the gas flow rate, the electron density increase and then discharge current will increase. Nitrogen gas has high internal energy over argon due to the dissociation reaction in the N_2 prior to ionization [10] and the dissociation energy for (Ar) is very small because of its van der waals bond type compared to that for N_2 of tripple bond type [12, 13].so; Nitrogen gas need to higher breakdown voltage than Argon gas where, V_{br} (N_2) =3.3kV, V_{br} (Ar) =2.7kV. See Fig. 2, where the discharge current in N_2 gas is greater than the discharge current in Argon gas and as the gas flow rate increase from (5-40) SCFH, the discharge current increase.

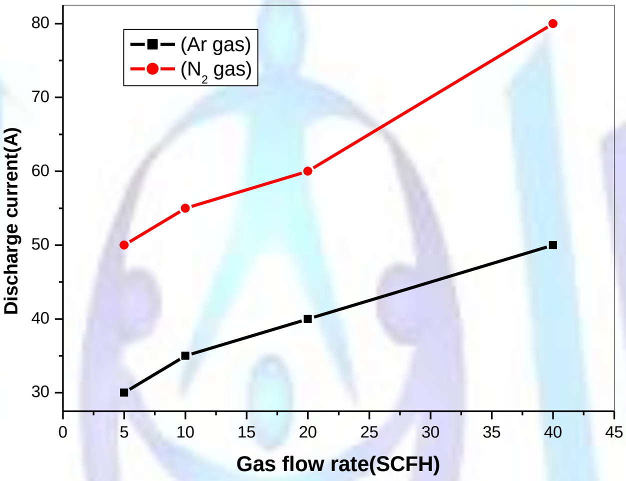

Fig. 2: Discharge current for Ar and N2 gases and flow rates.

It had seen from the experiment that the process of plasma formation of a two-atom (diatomic) gas differs from the process of plasma formation of a one-atom (mono-atomic) gas. The difference consists in the fact that the ionization of two-atom gas atoms starts after dissociation of its molecules. Nitrogen dissociates at a temperature of about 8500 K [11].an energy of 9.8 eV [12] which is required for rupturing the triple bond molecule of nitrogen while argon dissociate at a low eV values because its molecules constitute under the weak van der waals bond [13].

Figure3, shows the photographsof GAD plasma for different Argon gas flow rate at 2.7 kV discharge voltage and take these photographs at fixed distance (10 cm).

With increasing the gas flow rate, emission intensity increased in the upper-stream side. On the other hand, electric discharge area decreased with increasing gas flow rate in the downstream side. These results suggest that the upstream area is a positive column of the main arc discharge which can be controlled by discharge voltage, and downstream domain is GAD plasma which exists between electrodes that depend on the gas flow.

Fig. 3: photograph of GAD plasma for different argon gas flow rate at 2.7 kV discharge voltage.

Also, Figure4, shows the photograph of GAD plasma for different Nitrogen gas flow rate at 3.3 kV discharge voltage, take these photographs at fixed distance (10 cm).

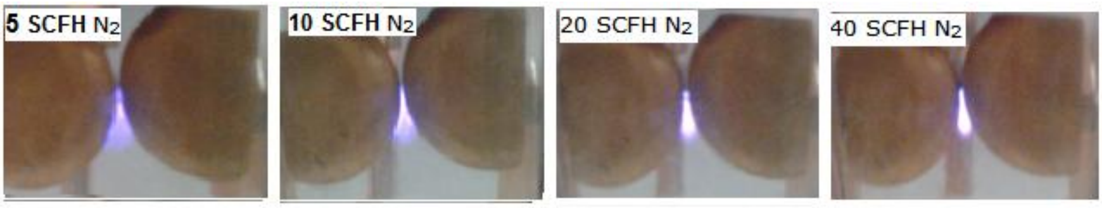

Fig. 4: photograph of GAD plasma for different Nitrogen gas flow rates at 3.3 kV discharge voltage.

It was observed from the previous photographs that in each case of Ar, N_2 the electric discharge area decreases with increasing the gas flow rate while the emission intensity increases with the gas flow rate. Also, it was observed that the emission intensity of N_2 GAD plasma at different flow rates is higher than the other in Ar GAD plasma. Also the plasma diversion or elongation in N_2 is more than in Ar. There are also products of GAD plasma like ozone (O_3), oxygen (O), hydroxil group (OH), hydrogen peroxide (H_2O_2) and ultraviolet rays (UV). These characteristics are important for applications like ozone generation, sterilization for environmental applications, and biomedical applications like cancer treatment.

All experimental results are tabulated in the shown Table 3.

Table. 3.Results of the comparison between Ar, N2 gases.

Comparison Faces	Ar gas				N_2 gas			
Flow rate(SCFH)	5	10	20	40	5	10	20	40
Charging voltage(kV)	2.7	2.7	2.7	2.7	3.3	3.3	3.3	3.3
Discharging current(A)	30	35	40	50	50	55	60	80
Power (kW)	81	95	108	135	165	181	198	264
Side drop (mm)	10 mm				12 mm			
Area S (cm^2)	1.5 cm^2				1.8 cm^2			
Current density (A /cm^2)	20	23.3	26.7	33.3	27.8	30.6	33.3	44.4
Electron density(cm^{-3})*10^{13}	2.7	4.4	6.8	9.8	1.9	2.6	3.7	8.5

Figure 5,shows an electron density of argon and nitrogen plasmas in gliding arc discharge (GAD) plasma at different gases flow rate (SCFH).

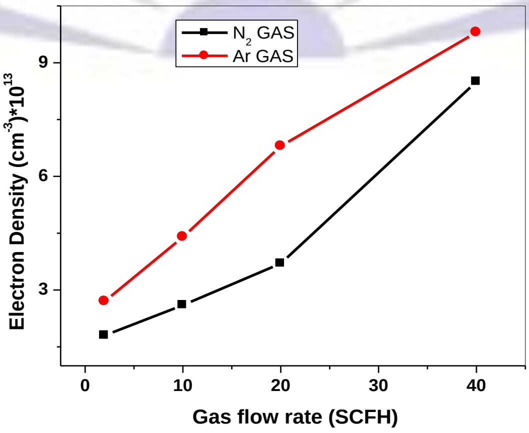

Fig. 5: Electron density as a function of argon and nitrogen gases flow rate

The discharge current increased with increasing gas flow rate (Ar and N2). This may be due to promotion of gas ionization by the gas flow rate increasing. In GAD plasma, high electric power density was applied to the gap electrode. Therefore, ionization is promoted with the increase in a gas flow and electron densities increased, and then discharge current increases.

Figures 6and 7,indicate that the GAD plasma area depend on the discharge current. As the discharge current increases, the GAD plasma area decreases while the electrical emission intensity increases (as shown the photographs in Fig. 3, Fig. 4).

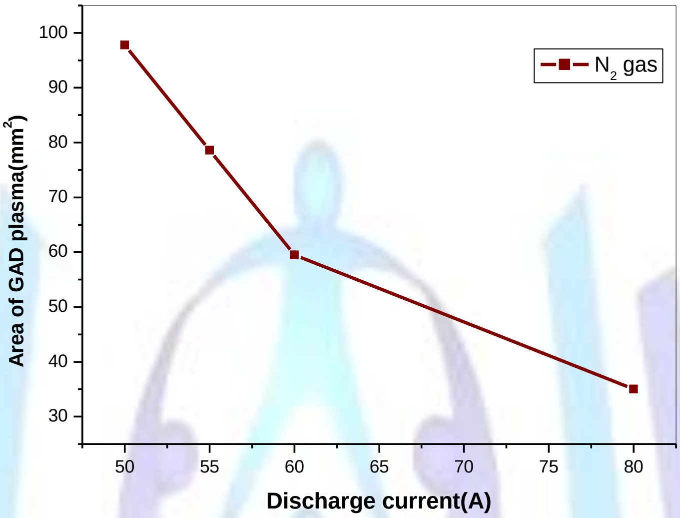

Fig. 6.Dependence of the GAD plasma Area of N$_2$gason discharge current

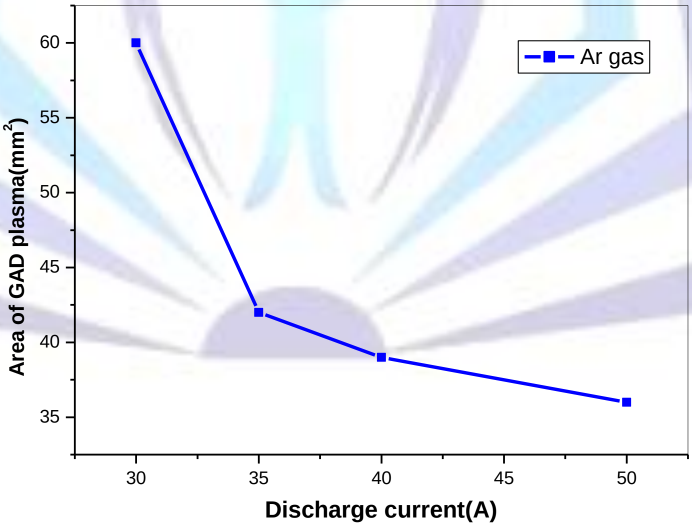

Fig. 7. Dependence of the GAD plasma Area of Ar gas on discharge current

Conclusion

Gliding Arc Discharge plasma has demonstrated the potential of combining advantages of both thermal and non-thermal plasmas for certain applications in optimized regimes.

The electron density of argon plasma (mono-atomic gas) is greater than nitrogen plasma (diatomic gas) because of the presence of negative ions in nitrogen plasma, the number of electrons is smaller in this case, which required the increase in discharge voltage of nitrogen in comparison with the argon plasma. Because of nitrogen an electronegative gas, the electron density number becomes smaller, decreasing electron density leads to increasing resistivity.

The streamer of GAD plasmawas represented using Ar, N_2 gases at different flow rates to show that the intensity of emitted light increases with increasing the flow rate which is important in certain applications.

All the results were tabulated in values obtained from calculation in comparison between Ar, N_2 to obtain the characteristics of each gas.

The device of GAD plasma can used in future in some vital and important applications: environmental applications like sterilization and gas cleaning, biomedical applications like plasma healing, blood co-agulation and cancer treatment.

Reference

[1] G. El-Aragi, Gliding Arc Discharge (GAD) Experiment, 19th International Symposium on Plasma Chemistry, Bochum, Germany,July (2009)

[2] Alexander F, Sergei N, Lawrence A K *et al*., Gliding arc discharge, Progress in Energy and Combustion Science, 25: 211–231,1999.

[3]Chiranjeev S. Kalra, Alexander F. Gutsol, and Alexander A. Fridman,Gliding Arc Discharges as a Source of Intermediate Plasma for Methane Partial Oxidation, *IEEE TRANSACTIONS ON PLASMA SCIENCE, VOL. 33, NO. 1,*F. (2005)

[4] Fridman, A., Gutsol, A., Gangoli, S., Ju, Y., and Ombrellol, Characteristics of gliding arc and its application in combustion enhancement,*J. Propul. Power*, 24 (6), 1216–1228,T. (2008)

[5] Benstaali, B., Boubert, P., Cheron, B., Addou, A., and Brisset, Density and rotational temperature measurements of the OH degrees and NO degrees radicals produced by a gliding arc in humid air. *Plasma Chem. Plasma Process.*,22(4), 553–571,J. (2002)

[6] Burlica, R., Kirkpatrick, M., and Locke, Formation of reactive species in gliding arc discharges with liquid water. *J. Electrostat.*, 64 (1), 35–43,B. (2006)

[7] Gangoli, S.P., Gutsol, A.F., and Fridman, A non-equilibrium plasma source: magnetically stabilized gliding arc discharge: I. Design and diagnostics. *Plasma Sources Sci. Technol.*, 19 (6), 065003, 2010

[8] Czernichowski A, Labbe P, Laval F, Lesueur emerging technologies in hazardous waste management [M].U.S. ACS Symp Series,1995.

[9] Yan J H, Du C M, Li X D *et al*., Plasma chemical degradation of phenol insolution by gas-liquid gliding arc discharge, Plasma Source Science and Technology, 14: 1–8,2005.

[10] D.A. Gerdeman and N. L. Hecht, Arc plasma technology in material science, Springer-Verlag, Wien and NY, 1972.

[11]Martinek, f. “thermodynamic and electrical properties of nitrogen at high temperatures”International symposium on thermal properties, Indiana, P.130, 1959

[12] R. Bartinkas "Engineering Dielectrics volume 111, Electrical Insulating Liquids" ASTM Publication code number (PCN) varennes, sept 18, 1991

[13] T. J. Lewis and P. E .Secker "Since of Materials" George G. Harrap & LTD, London Toronto wellington Sydney, 1966

[14]burn horn,f.,wienecke, R.Z.physik.chem.,215, P.269,1960

[15]BusJ.G., Peuckert,w.,Finkelnburg,w.z.physik,144,P.244,1956

[16] Y. P. Raizer, Gas Discharge Physics ,Springer, New York,p. 11,1991