ELECTRICAL CHARACTERISTICS SIMULATION OF HOMOGENEOUS DBD AT ATMOSPHERIC PRESSURE. APPLICATION TO HELIUM AND ARGON PLASMAS.

Roukia ABIDAT, Saïda REBIAI

Microsystems and Instrumentation Laboratory (LMI), Electronic Departement, Engineering Faculty,

Université fréres Mentouri Constantine, Algeria

Reçu le 18 Juillet 2017 – Accepté le 12 novembre 2017

Abstract

Homogeneous discharges are easily obtained at atmospheric pressure in dielectric barrier discharges (DBD) for some noble gases. To predict the discharge electrical comportment, one-dimensional fluid model of typical DBD is presented and applied to Helium and Argon discharges. The first two moments of Boltzmann equation (continuity and momentum (drift-diffusion approximation)) are coupled with Poisson's equation by the finite element method (FEM) using COMSOL Multiphysics software. In this work, the simulation is carried out using the same operating conditions for helium and argon gases. The electrical characteristics of the DBD, simulated by the proposed model, allow, by simple calculations, the access and the analysis of other discharge parameters such as Lissajous figures, consumed power and charge density. The obtained characteristics are assigned to the largely explained homogeneous discharges and are consistent with the experimental ones reported in the literature for both gazes. The effect of gas spacing and applied frequency on the electric characteristics has been also investigated. It has been found that for the considered range of frequency (25-200 KHz) and gap distance (2-5 mm); only one current peak is observed. The results indicate that increasing gas space or decreasing applied frequency lead to a diminishing in pulse intensity and a rise breakdown voltage**.**

***Keywords**: Atmospheric pressure; plasma DBD; Fluid model; Electrical characteristics; ; Homogeneous mode; glow mode; pseudo glow ;Lissajous.*

Résumé

Des décharges homogènes sont facilement obtenues à la pression atmosphérique dans des décharges à barrière diélectrique (DBD) pour certains gaz rares. Pour prédire le comportement électrique de la décharge, un modèle de fluide unidimensionnel du DBD typique est présenté et appliqué aux décharges d'hélium et d'argon. Les deux premiers moments de l'équation de Boltzmann (continuité et moment (approximation de la dérive-diffusion)) sont couplés à l'équation de Poisson par la méthode des éléments finis (FEM) à l'aide du logiciel COMSOL Multiphysics. Dans ce travail, la simulation est réalisée en utilisant les mêmes conditions de fonctionnement pour les gaz d'hélium et d'argon. Les caractéristiques électriques du DBD, simulées par le modèle proposé, permettent, par de simples calculs, l'accès et l'analyse d'autres paramètres de décharge tels que les valeurs de Lissajous, la puissance consommée et la densité de charge. Les caractéristiques obtenues sont attribuées aux décharges homogènes largement expliquées et sont cohérentes avec celles expérimentales rapportées dans la littérature pour les deux gaz. L'effet de l'espacement des gaz et de la fréquence appliquée sur les caractéristiques électriques a également été étudié. Il a été constaté que pour la gamme de fréquences considérée (25-200 KHz) et l'espacement (2-5 mm); un seul pic de courant est observé. Les résultats indiquent que l'augmentation de l'espace gazeux ou la diminution de la fréquence appliquée entraînent une diminution de l'intensité des impulsions et une augmentation de la tension de rupture.

***Mots clés**: Pression atmosphérique; DBD plasmatique; Modèle fluide; Caractéristiques électriques; ; Mode homogène; mode lueur; pseudo lueur; Lissajous.*

ملخص

يتم الحصول بسهولة على تصريفات متجانسة عند الضغط الجوي في تصريفات حاجز عازل (DBD) لبعض الغازات النبيلة. للتنبؤ بالمغادرة الكهربائية للتصريف ، يتم تقديم نموذج السائل أحادي البعد لنموذج DBD وتطبيقه على تصريفات الهيليوم والارجون. تقترن أول لحظتين لمعادلة بولتزمان (الاستمرارية والزخم (تقريب الانتشار العاري)) مع معادلة بواسون باستخدام طريقة العناصر المحددة (FEM) باستخدام برنامج COMSOL Multiphysics. في هذا العمل ، تتم المحاكاة باستخدام نفس ظروف التشغيل لغاز الهيليوم والأرجون. تسمح الخصائص الكهربائية لـ DBD ، المحاكاة بالنموذج المقترح ، من خلال الحسابات البسيطة ، الوصول إلى وتحليل معلمات التفريغ الأخرى مثل أرقام Lissajous ، استهلاك الطاقة وكثافة الشحنة. يتم تعيين الخصائص التي تم الحصول عليها إلى تصريفات متجانسة إلى حد كبير وأوضح متسقة مع تلك التجارب التي ذكرت في الأدبيات لكل من gazes. كما تم دراسة تأثير المباعدة بين الغازات والتردد التطبيقي على الخصائص الكهربائية. وقد وجد أنه بالنسبة لمدى التردد المدروس (25-200 KHz) ومسافة الفجوة (2-5 ملم) ؛ لوحظت ذروة واحدة الحالية. تشير النتائج إلى أن زيادة مساحة الغاز أو خفض الترددات المطبقة يؤدي إلى تناقص كثافة النبض وارتفاع الجهد الكهربائي.

***الكلمات المفتاحية:** الضغط الجوي؛ بلازما دي دي دي نموذج السوائل الخصائص الكهربائية؛ . وضع متجانس وضع توهج توهج زائف ؛ .Lissajous.*

1. INTRODUCTION

Dielectric barrier discharge (DBD) at atmospheric pressure has become more relevant in engineering and science because it is an effective method to produce cold and non-equilibrium plasma in atmospheric pressure. Nowadays DBD found numerous applications such as ozone generation, excitation of CO_2 laser [1-2], etching, deposition and structural modification of polymeric surfaces [3-4], Excimer lamps [5], plasma chemical vapor deposition [6], pollution control [7], plasma display panels (PDPs) [8], surface plasma actuators (SDBD) [9-10] and medical applications[11-13].

The DBD name derives from the fact that, at least, a dielectric layer covers one or both electrodes. This dielectric layer, placed on the electrode surface, is in contact with the discharge (SDBD) or in the space between electrodes (DBD). It can be made from glass, quartz, ceramic, or polymer materials [14].

The DBD characteristics have been experimentally and numerically investigated for various gases, particularly for pure helium [15-16], pure argon, helium or argon with small addition of N_2, O_2 [17-21], other gases and air [22-25]. The aim of choosing helium and argon gases in atmospheric DBD plasma is to produce stable and homogeneous discharges much easier compared with other reactive gases.

The studies of traditional DBDs have shown that DBDs exhibit different processes and discharge modes due to different discharge conditions [16, 18, 26-27].

In this work, one-dimensional fluid model using COMSOL Multiphysics software is formulated to give a simple simulation of a DBD and present a synthesis of the influence of the operating conditions on the electrical characteristics of these discharges, considering helium and argon gases. COMSOL modeling provides especially the spatial distribution of all species considered as a function of time, as well as the potential and electric field at each point of the solved domain. The software is based on the finite element method [28]. It also exhibits results such discharge gas voltage, voltage–current (V-I) characteristics and consumed power ….etc, which are not directly accessible experimentally.

In this paper, we focus our discussion on the effect of gap distance and applied frequency on the most important electrical parameters, which give some information on the DBD modes.

2. DESCRIPTION OF COMPUTATIONAL MODEL :

The geometric model presented in this simulation work is similar to the reactor used for the Escherichia coli inactivation [29-31] shown in figure 1. It consists of two parallel and circular metal electrodes of 10 mm thickness and 100 mm diameter. The lower electrode is covered with a dielectric with a thickness of 1.3 mm and a relative permittivity of 10. The DBD is driven by a sinusoidal voltage. The discharge gap distance is L= 3 mm. In this DBD modeling, we assume that the discharge region is filled with pure helium or pure argon plasma.

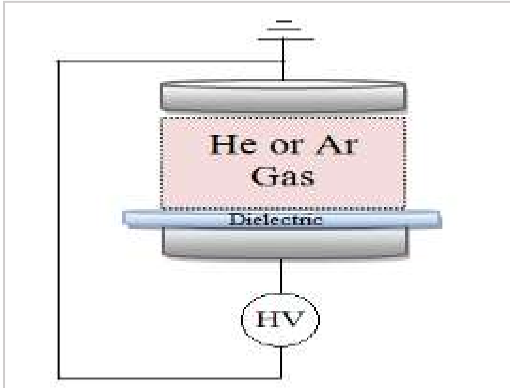

Fig.1 Schematic diagram of the parallel-plate DBD reactor with one dielectric barrier.

The particles taken into account in this modeling are electrons, ground state atoms, ions and excited atoms. The numerical simulation is based on one dimensional (1D) fluid model that consists in solving the first two momentums of the Boltzmann equation coupled to Poisson's equation.

The discharge plasma is governed by:

- The continuity equation :

$$\frac{\partial n_k}{\partial t} + \nabla(\Gamma_k) = S_k \quad (1)$$

- The drift-diffusion approximation, as:

$$\Gamma_e = -n_e \mu_e E - \nabla(n_e D_e) \quad (2)$$

$$\Gamma_p = n_p \mu_p E - \nabla(n_p D_p) \quad (3)$$

$$\Gamma_* = -\nabla(n_* D_*) \quad (4)$$

- Poisson's equation:

$$\Delta V = \frac{q}{\varepsilon_0}(n_e - n_i) \qquad \text{And} \qquad E=-\nabla V \quad (5)$$

Where n_k, Γ_k and S_k are the particle density, the flux and the source terms of particles k (k = e, p,*), respectively. Source terms are calculated with the reactions and corresponding reaction rates. Subscripts e, p, and * represent electrons (e), positive ions and metastable species, respectively. E is the electric field. μ_k and D_k are mobility and diffusion coefficient of species, respectively. V is the electrostatic potential, ε_0 is the vacuum permittivity, q is the elementary charge and t is the time.

- ***Boundary and initial conditions:***

a) The electron flux to the electrodes and all reactor walls :

$$-n.\Gamma_e = \frac{1}{2} V_{e,th} n_e - \sum_p \gamma_p (\Gamma_p . n) \qquad (6)$$

γ_p is the secondary electron emission coefficient and n is the unit normal vector to the wall. $V_{e,th}$ is the electron thermal velocity, given as:

$$V_{e,th} = \sqrt{\frac{8 K_B T_e}{\pi . m_e}} \qquad (7)$$

Where K_B is the Boltzmann constant, Te is the electrons temperature and me is the electron mass.

***b) Surface charge accumulation*:**

In DBD reactors, surface charge accumulation is produced at the dielectric surface which is adjacent to the gap where the plasma is created. This phenomenon leads to the following boundary conditions on the dielectric barriers:

$$n.(E1.\varepsilon 1 - E2.\varepsilon 2) = \rho \qquad (8)$$

Where E_1 and E_2 denote the electric field at the dielectric gas interface and ε_1 and ε_2 are the relative permittivity of the gas and the dielectric, respectively. ρ is the charge density.

c) Electric potential :

The calculation is carried out for a sinusoidal external voltage (V):

$$V = V_{rf} \sin(2\pi f t) \qquad (9)$$

Where V_{rf} is the amplitude of applied voltage and f its frequency.

d) initial values

Initial values used in this simulation are:

- Initial electron density $n_{e,0}$ which represents a small number of seed electrons assumed to be present in the gap : $n_{e,0}=10^6$ (1/m³).
- Initial mean electron energy : $\bar{\varepsilon} = 5\,(V)$

Particle interactions considered in this model include volumetric and surface excitations, direct ionization, Penning ionization elastic electron-atom collision and metastable quenching. The cross-sectional data of the electron-helium and electron-argon collisions required to perform the simulations are obtained from the Boltzmann BOLSIG code [32].

3. RESULTS AND DISCUSSIONS

The spatiotemporal characteristics of DBD in argon and helium have been numerically studied. The simulation is carried for atmospheric pressure, external voltage amplitude V_{rf} of 1 kV, external voltage frequency of 50 kHz and a gas temperature equal to 400 K. The secondary electron emission coefficient is set at 0.01.

Figure 2 and figure 3 show the time evolution of the calculated electrical characteristics and distribution of electron density during two cycles for applied voltage. For both gases, the current and gas voltage waveforms present a single peak by half cycle of applied voltage.
From these figures, the comparison of the discharge current waveforms obtained for these DBD indicates that helium current peaks are higher in amplitude (about 0.3 A) than argon current peaks (about 0.1 A). We can also see that the current characteristics present shorter discharge duration for helium (about 1.2 µs and 1.6 µs for argon). In addition, in argon current waveform, we can see, after the large peak, a small increase in current representing the named residual current peak [15].

These results indicate that the discharge modes are homogeneous since the pulse durations are more than the nanosecond obtained for a filamentary mode. It is consistent with several simulations and experimental works on homogeneous barrier discharges in helium and argon or other gases with different working conditions [5, 15, 18- 19, 27, 33- 35].

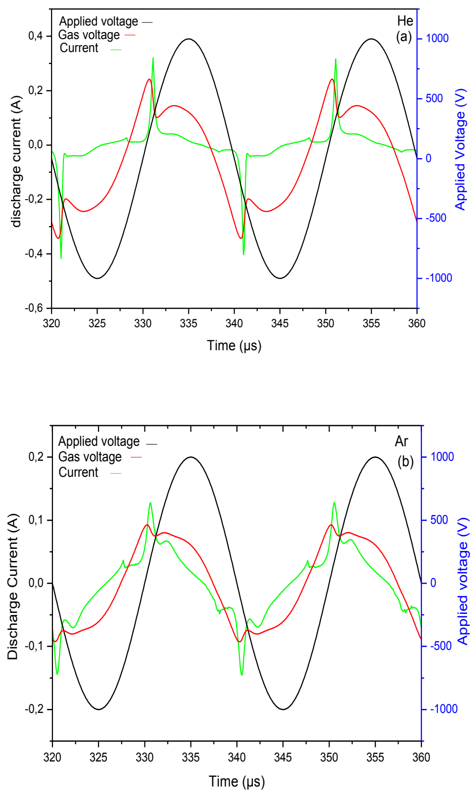

Fig.2 Time evolution of discharge current and gas voltage during two cycles of applied voltage in:(a) helium, (b) argon for V_{rf} = 1kV, f= 50 kHz and a gap distance of 3 mm.

Furthermore, we see from this figure that gas voltage evolution follows discharge current variation. The gas voltage characteristics present a rapid drop at the same moment the current peak appears and increase again following the current pulse. The corresponding breakdown voltages are about 460 V for argon and 660 V for helium DBD.

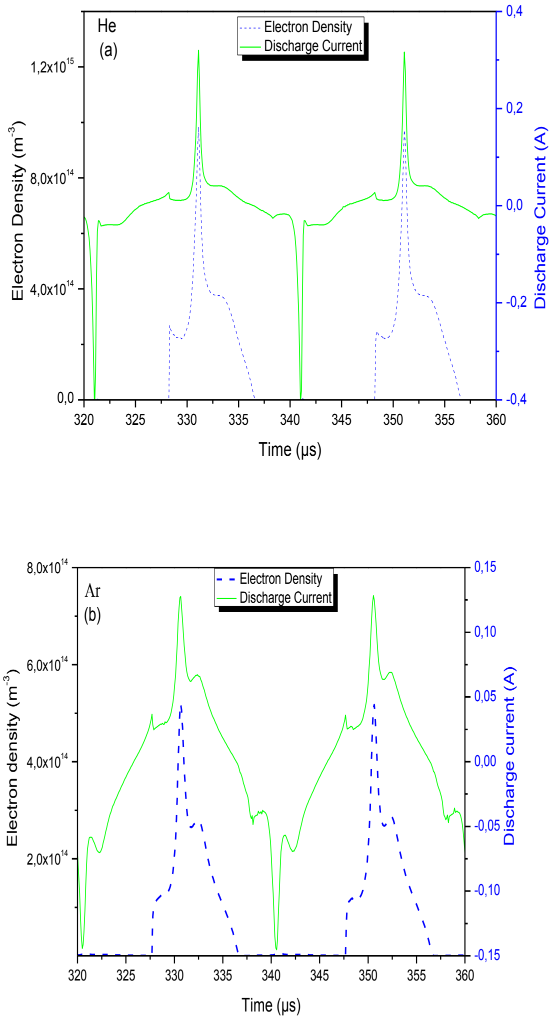

Fig 3.Time evolution of electron density: (a) for helium and (b) argon DBDs for V_{rf} = 1kV, f= 50kHz and a gap distance of 3 mm.

The evolution of electron densities versus discharge current characteristics are illustrated in figures 3. This figure confirms the presence of higher peaks in helium DBD by the elevated value of electron density. The breakdown appears for an electron density of about 10^{15} m^{-3} in helium and $5x10^{14}$ m^{-3} in argon. The small increase observed I_d (t) for argon corresponds to an electron density of $2x10^{10}m^{-3}$ indicating that this number of electrons, in argon at working conditions, is sufficient to maintain a glow process of the first peak and to produce a second breakdown.

Another way to investigate the evolution of the gas voltage is to analyze its variation as a function of the discharge current with the typical voltage -current characteristic. This characteristic is illustrated in figures 4 (a) and (b) for the positive alternation of the applied voltage, for helium and argon, respectively.

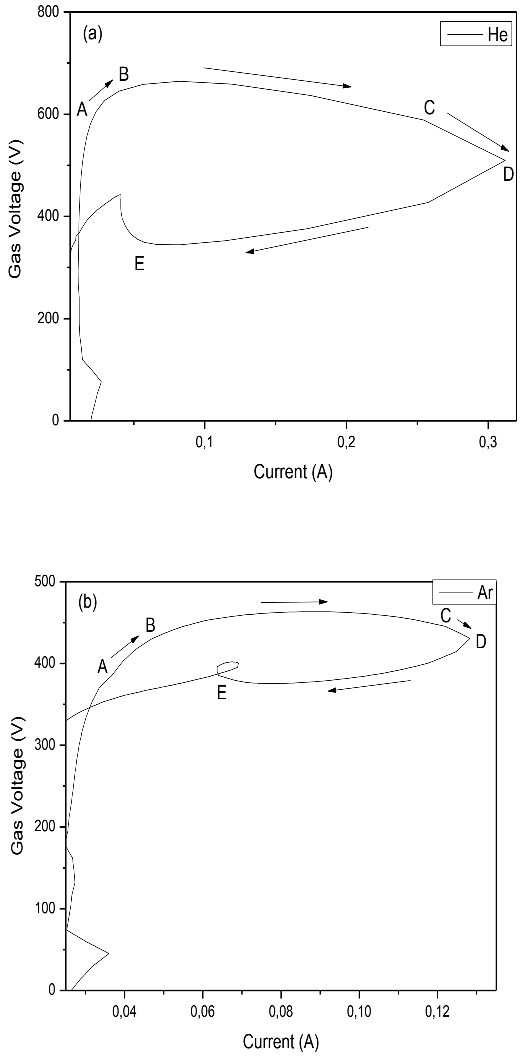

Fig.**4**. Voltage-Current (V-I) curves of atmospheric pressure DBD: (a) in helium and (b) in argon

From this figures it's clear that the obtained I-V curves present only one ring during the current evolution by alternation, corresponding to a single current peak by half cycle characteristics of an APGD [27, 36].

In DBD helium, figure 4 (a) shows that the gas voltage increases significantly (from zero point Voltage to point A) with very small increase of the discharge current. While the gas voltage is still increasing, the discharge current undergoes a low increase to point B. In this part, we have a non-self-sustained discharge and a current due to the external source until breakdown in point B. From B to C, gas voltage remains constant (breakdown voltage) while the current continue to increase, according to the Townsend regime. Beyond the point C, the gas voltage decreases by more than 15 % until point D where the current reaches its maximum value. The evolution from point C to point D corresponds to a subnormal glow discharge. Elsewhere, for argon DBD, the evolution of I (V) characteristic illustrated in figure 4 (b) shows some differences. Effectively, after the breakdown in point B, the Townsend phase B-C is more important and the subnormal glow C-D presents a decrease in gas voltage only of 4%, where the current reaches its maximum in point D. in addition, argon I-V curve present a small ring at a current of 0.07A corresponding to the small second pulse.

The proposed model also allows the investigation of the charge-voltage Lissajous figures. This characteristic is a standard means of the electrical diagnostic of DBD discharge due to the important information that contains.

Lissajous simulated curves are illustrated in figure 5 for argon and helium homogeneous dielectric barrier discharges. These curves present clear steps at each perpendicular edges corresponding to peaks of current characteristics (positive and negative alternations). The form of this Lissajous figures for a single current peak of homogeneous DBD is not an ideal parallelogram.

The dissipated energy per cycle of the applied voltage has been calculated using the area of the Lissajous according to the following relation [37]:

$$E(L) = \int Q.dV = A_{Lissajous} \tag{10}$$

Where Q is the surface charge density and $A_{Lissajous}$ is the surface area of the Lissajous figure.

To calculate this energy from simulated curve (Q-V) we have used Trapez method for integration and compared the results with OriginPro 8 tools.

The power consumed by the discharge can also be investigated. This power was calculated as the product of V_g (gas voltage) and I_d (discharge current).

The power consumed by the discharge as a function of time is presented in figure 6. It may be noted that this power for helium DBD is greater than for argon.

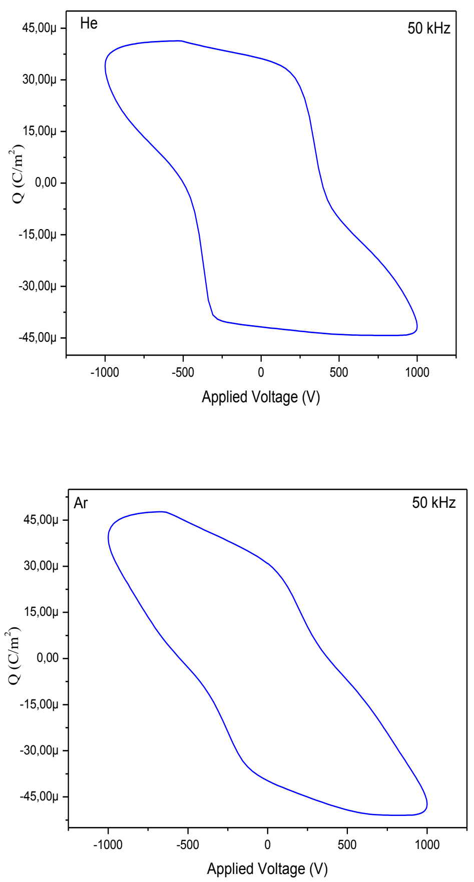

Fig.5. Lissajous figure for an applied voltage of 1kV, a frequency of 50 kHz and a gap distance of 3 mm for argon and helium DBDs

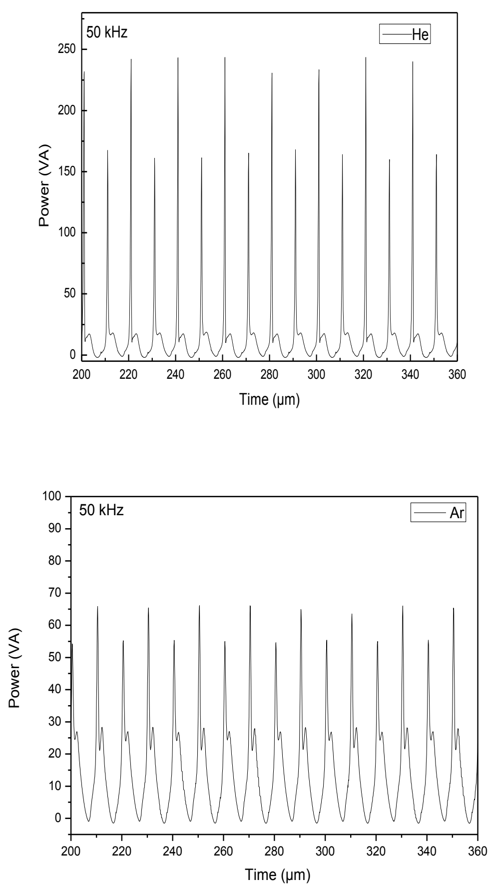

Fig. 6 Evolution of power in helium and argon DBDs for an applied voltage of 1kV, a frequency of 50 kHz and a gap distance of 3 mm.

4. INFLUENCE OF DBD REACTOR PARAMETERS :

The mode of the discharge characteristics in DBD reactor depends strongly on operation parameters of the discharge system, such as gap distance, dielectric barrier thickness and nature of insulating layer material, nature of gas and amplitude and frequency of external voltage.

A simple simulation with the elaborated model allows the study of the effect of the reactor's parameters on the characteristics of the discharge. In this section, we present an investigation illustration on the effects of gap distance and applied frequency on current characteristics, gas voltage, calculated Energy and consumed power.

A. *Influence of gap distance :*

The effect of discharge gap on the electric characteristics of argon and helium DBDs is depicted for an electrode spacing varying from 2 to 5 mm, an applied voltage of 1kV, a frequency of 50 kHz and a constant dielectric of the insulating layer maintained constant, equal to 10.

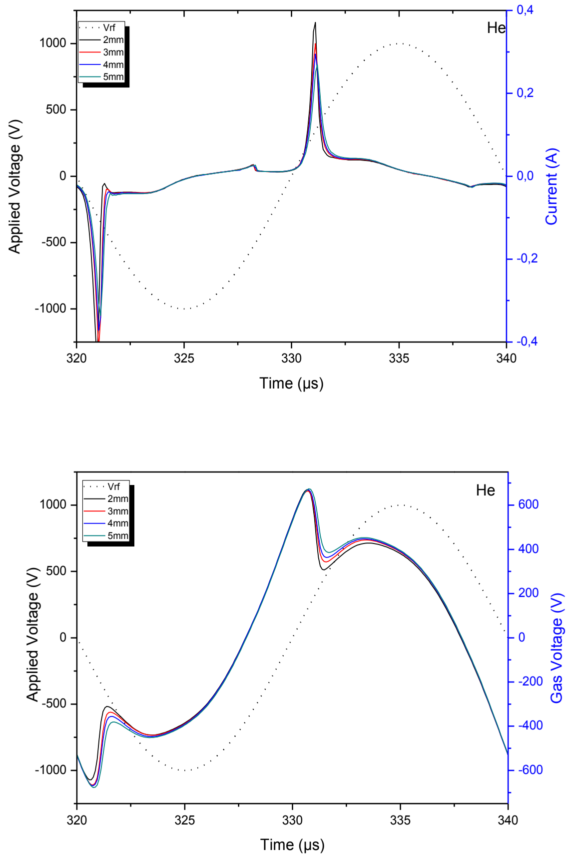

Fig.7. Current and gas voltage characteristics for different value of gap distance L= 2mm; 3mm; 4mm and 5mm for Helium plasma.

Figures 7 and 8 show the simulated characteristics. it is clearly seen that varying gap distance from 2 to 5 mm produces a small decrease in current peaks intensity (from 0.36 to 0.26 A for helium and from 0.13 to 0.10 A for argon) and a little increase of the amplitude of breakdown voltage (from 668to 674 V for helium and from 453 to 485V for argon). In addition, an increase of discharge duration results in increasing gap distance.

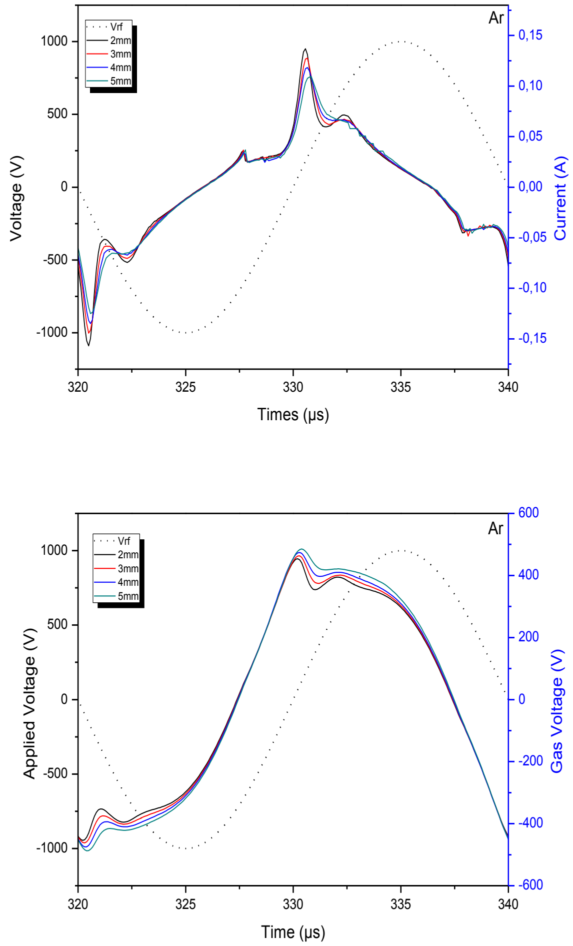

Fig.8. Current and gas voltage characteristics for different value of gap distance L= 2mm; 3mm; 4mm and 5mm for argon plasma.

The obtained values of dissipated energy calculated for electrode spacing varying from 2 to 5mm are presented in figure 9. The results indicated that for both gases, the dissipated energy increase with increasing gap distance between electrodes. The dissipated energy values were in the same order of magnitude for helium and argon.

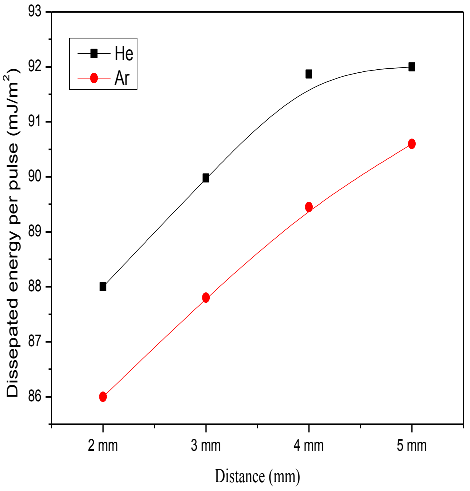

Fig 9. Dissipated energy per pulse for an applied voltage of 1kV, a frequency of 50 kHz and a gap distance of 2 to 5mm.

B. *Influence of Applied Frequency*

In this section, we present a simulation of the influence of the external driving frequency on the dynamic behavior of the discharge characteristics of helium and argon DBDs. The electric characteristics Id (t) and Vg (t) are calculated for applied frequency values varying from 25 to 200 kHz, applied voltage of 1 kV and electrode spacing fixed at 3 mm.

Figures 10 and 11 show the result of simulation. From this figures, it is clearly observed that only one current peak is maintained by half cycle of applied voltage for the considered range of driving frequency. This behavior indicated that at this frequency the time is not sufficient to produce pseudo glow discharges. The current peaks amplitude decreases when applied frequency changes from 25 to 50 KHz then increases with driven frequency until 200 KHz. Elsewhere, this evolution of discharge current leads to a decrease of breakdown voltage and an increase of discharge duration as the external driven frequency rises. The same phenomenon is observed for the two DBD gases.

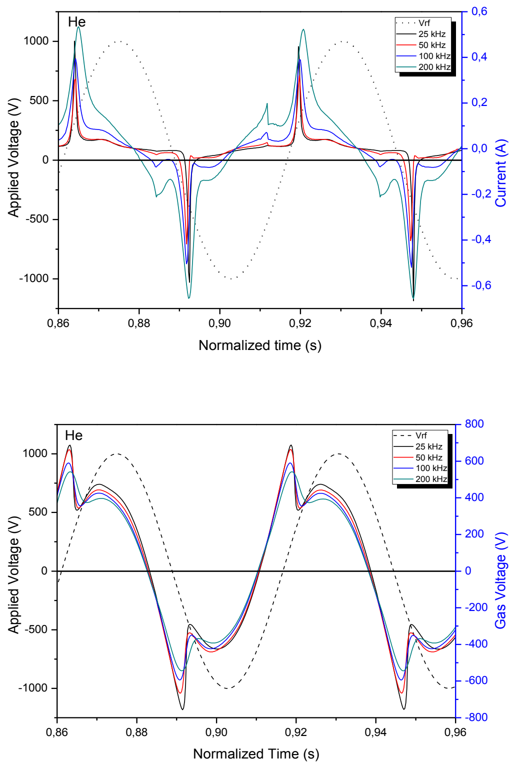

Fig.10.Current and gas voltage characteristics for different value of external driving frequency varying from 25 to 200 kHz for helium plasma

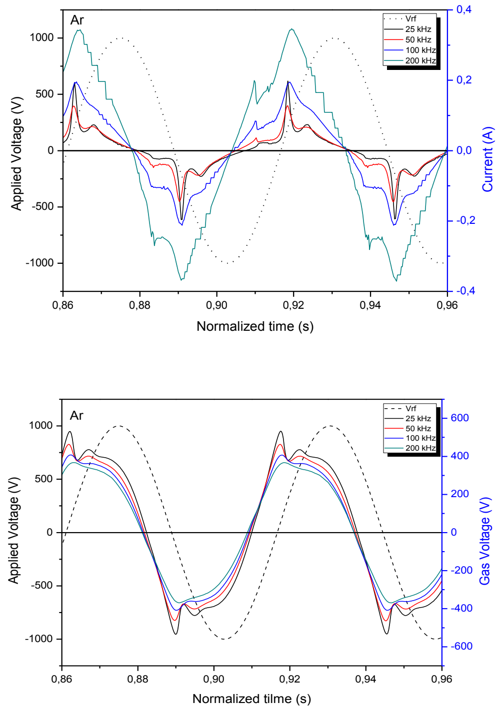

Fig.11.Current and gas voltage characteristics for different value of external driving frequency varying from 25 to 200 kHz for argon plasma

The effect of the driving frequency on dissipated energy (DE) during an applied voltage cycle is illustrated in figure 12. The results show that, rising driven frequency produce an increase of dissipated energy for 25 to 100 KHz followed by pseudo saturation until 200 KHz. The evolution of this characteristic seems to be the same for both gases.

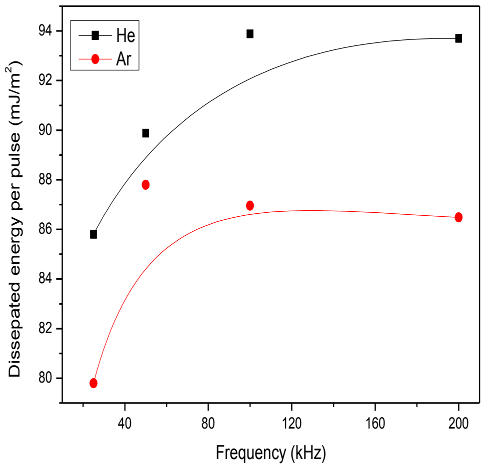

Fig.12 Dissipated energy per pulse for a gap distance of 3 mm, applied voltage of 1kV and driven frequency varying from 50 kHz to 200 kHz.

5. CONCLUSION

In this study, electrical characteristics of helium and argon homogeneous discharges in atmospheric pressure with dielectric barrier have been theoretically simulated. The theoretical model has been solved by the finite element method using COMSOL Multiphysics software.

This simple model is elaborated to illustrate the evolution of different discharge characteristics in homogeneous mode. For example, we have applied the developed model to the study of the influence of driving frequency amplitude and gap distance on the discharge characteristics of helium and argon DBD. The results of the simulation revealed that:

The simulated characteristics of helium and argon plasmas are consistent with the experimental ones reported in the literature. Current waveforms are typical of homogeneous DBD distinguished by the presence of a single peak by half cycle of applied voltage.

Increasing gap distance from 2 to 5 mm leads to a diminishing in pulse intensity and a rise in breakdown voltage. On the contrary, this effect is observed with decreasing driving frequency values from 200 to 25 KHz. However, the increase of the two parameters leads to an increase of pulse duration.

REFERENCES

[1] U. Kogelschatz, “Dielectric-barrier discharges: Their history, discharge physics and industrial applications,” Plasma Chem. Plasma Process. vol. 23, no. 1, pp. 1–46, Mar. 2003.

[2] U. Kogelschatz, “From ozone generators to flat television screens: history and future potential of dielectric-barrier discharges“, Pure Appl. Chem. 7 (1999).

[3] Cheng Zhang, Tao Shao, Member, IEEE, Kaihua Long, Yang Yu, Jue Wang, Dongdong Zhang, Ping Yan, Member, IEEE, and Yuanxiang Zhou, Member, IEEE “Surface Treatment of Polyethylene Terephthalate Films Using DBD Excited by Repetitive Unipolar Nanosecond Pulses in Air at Atmospheric Pressure “IEEE Transactions On Plasma Science, Vol. 38, No. 6, June 2010.

[4] Yunfei Liu, Chunqiang Su, Xiang Ren, Chuan Fan, Wenwu Zhou,Feng Wang, Weidong Ding," Experimental study on surface modification of PET films under bipolar nano second-pulse dielectric barrier discharge in atmospheric air", Applied Surface Science, Vol. 313, pp. 53–59, 2014.

[5] Halima Loukil, Ahmed Belasri, Khadija Khodja, and Zahir Harrache, "Theoretical Kinetics Investigation of Xenon Dielectric Barrier Discharge for Excimer Lamp",IEEE Transactions On Plasma Science, Vol. 42, No. 3 March 2014.

[6] Julien Vallade, Remy Bazinette, Laura Gaudy and Francoise Massines," Effect of glow DBD modulation on gas and thin film chemical composition case of $ArSiH_4NH_3$ mixture", J. Phys. D: Appl. Phys. 47 (2014) 224006.

[7] H. Than Quoc An, T. Pham Huu, T. Le Van, J.M. Cormier, A. Khacef," Application of atmospheric non thermal plasma-catalysis hybrid system for air pollution control: Toluene removal" Catalysis Today 176 (2011) 474– 477.

[8] P P Zhang, Y Tu and L L Yang, "The relationship between the distribution of anode striations and negative and positive charge accumulation in a plasma display panel", Plasma Sources Sci. Technol. 20 (2011) 065004.

[9] Gabriele Neretti, Andrea Cristofolini, and Carlo A. Borghi , "Experimental investigation on a vectorized aerodynamic dielectric barrier discharge plasma actuator array", Journal Of Applied Physics 115, 163304 (2014).

[10] M. Abdollahzadeh a,b, J. C. Páscoa a, P.J. Oliveira b, "Two -dimensional numerical modeling of interaction of micro-shock wave generated by nanosecond plasma actuators and transonic flow ",Journal of Computational and Applied Mathematics 270 (2014) 401–416.

[11] Halim Ayan, Gregory Fridman, David Staack, Alexander F. Gutsol, Victor N. Vasilets, Alexander A. Fridman, and Gary Friedman," Heating Effect of Dielectric Barrier Discharges for Direct Medical Treatment ", IEEE Transactions On Plasma Science, Vol. 37, No. 1, January 2009.

[12] Th. von Woedtke, S. Reuter , K. Masur, K.-D. Weltmann," Plasmas for medicine ", Physics Reports 530 (2013) 291–320.

[13] Kiara Heuer , Martin A. Hoffmanns , Erhan Demir , Sabrina Baldus , Christine M. Volkmar , Mirco Rohle , Paul C. Fuchs , Peter Awakowicz , Christoph V. Suschek , Christian Oplander," The topical use of non-thermal dielectric barrier discharge (DBD) Nitric

oxide related effects on human skin 2015 ", Nitric Oxide 44 (2015) 52–60.

[14] A.Chirocov, A. Gutsol, and A. Fridman, "Atmospheric pressure plasma of dielectric barrier discharge." pure, Appl. Chem., vol. 77, no.2, pp. 487-495, 2005.

[15] Zhi Fang, Shengchang Ji, Jun Pan, Tao Shao, and Cheng Zhang, "Electrical Model and Experimental Analysis of the Atmospheric-Pressure Homogeneous Dielectric Barrier Discharge in He" IEEE Transactions On Plasma Science, Vol. 40, No. 3, March 2012.

[16] Xiaolong Wang, Zhenyu Tan, Lanlan Nie, and Jie Pan, "Study on Modes of the Pulsed Dielectric Barrier Discharges at Atmospheric Pressure in Helium", IEEE Transactions On Plasma Science, Vol. 42, No. 9, September 2014.

[17] Zhiyuan Hao, Shengchang Ji, Member, IEEE, and Aici Qiu, "Study on the Influence of Dielectric Barrier Materials on the Characteristics of Atmospheric Plasma Jet in Ar", IEEE Transactions On Plasma Science, Vol. 40, No. 11, November 2012.

[18] Dongsoo Lee, Jin Myung Park, Sang Hee Hong, Member, IEEE, and Yongho Kim, Member, IEEE, "Numerical Simulation on Mode Transition of Atmospheric Dielectric Barrier Discharge in Helium–Oxygen Mixture", IEEE TRANSACTIONS ON PLASMA SCIENCE, VOL. 33, NO. 2, APRIL 2005.

[19] Xinxin Song, Zhenyu Tan, and Bo Chen, «Study on the Characteristics of Atmospheric Dielectric Barrier Discharges in He−N_2 Admixture", IEEE Transactions On Plasma Science, Vol. 40, No. 12, December 2012.

[20] LIU Zhongwei, YANG Lizhen, WANG Zhengduo,SANG Lijun, ZHU Qiang , LI Sen, "Atmospheric Pressure Radio Frequency Dielectric Barrier Discharges in Nitrogen/Argon", Plasma Science and Technology, Vol.15, No.9, Sep. 2013.

[21] A.S. Chiper, G.B. Rusu, C. Vitelaru, I. Mihaila and G. Popa, "Comparative Study Of Helium And Argon DBD Plasmas Suitable For Thermosensitive Materials Processing", Rom. Journ. Phys., Vol. 56, Supplement, P. 126–131, Bucharest, 2011.

[22] Abasalt Hosseinzadeh Colagar[a,b,*], Farshad Sohbatzadeh[b,c],Saeed Mirzanejhad[b,c], Azadeh Valinataj Omran[a,c], "Sterilization of Streptococcus pyogenes by afterglow dielectric barrier discharge using O_2 and CO_2 working gases", Biochemical Engineering Journal 51 (2010) 189–193.

[23] Xiao Lei and Zhi Fang, "DBD Plasma Jet in Atmospheric Pressure Neon", IEEE Transactions On Plasma Science, Vol. 39, No. 11, November 2011.

[24] Antonis P. Papadakis, "Numerical Analysis of the Heating Effects of an Atmospheric Air-Dielectric Barrier Discharge ",IEEE Transactions On Plasma Science, Vol. 40, No. 3, March 2012.

[25] Svetlana V. Avtaeva, "About Formation of Secondary Current Pulses in Dielectric Barrier Discharges in Xe-Cl_2 Mixtures", IEEE Transactions On Plasma Science, Vol. 42, No. 1, January 2014.

[26] Martens, W J M Brok, J van Dijk and A Bogaerts, "On the regime transitions during the formation of an atmospheric pressure dielectric barrier glow discharge ",J. Phys. D: Appl. Phys. 42 (2009) 122002 (5pp).

[27] F Massines, N Gherardi, N Naudé and P S´egur, "Glow and Townsend dielectric barrier discharge in various atmosphere", Plasma Phys. Control. Fusion 47 (2005) B577–B588.

[28] www.comsol.com.

[29] Lyes Benterrouche, Salah Sahli, Saida Rebiai and Abdellah Benhamouda "Inactivation of E–coli bacteria by atmospheric dielectric barrier discharge", Int. J. Nanotechnology, Vol. 10, Nos. 5/6/7, 2013.

[30] Roukia ABIDAT, Saïda REBIAI, Lyes BENTERROUCHE," Numerical Simulation of Atmospheric Dielectric Barrier Discharge in Helium gas using COMSOL Multiphysics", Proceedings of the 3rd International Conference on Systems and Control, Algiers, Algeria, October 29-31, © 2013 IEEE.

[31] Roukia ABIDAT, Saïda REBIAI, «A modeling of atmospheric DBD parameters effect on plasma electrical characteristics ",Proceedings of The first International Conference on Nanoelectronics, Communications and Renewable Energy 2013

[32] BOLSIGS, Boltzmann Solver for the SIGLO series 1.0 CPA Toulous Kinema Software,1996.

[33] Yu B Golubovskii1, V A Maiorov, J Behnke and J F Behnke "Modelling of the homogeneous barrier discharge in helium at atmospheric pressure" J. Phys. D: Appl. Phys. 36 (2003) 39–49.

[34] F. Massines, A. Rabehi, P. Decomps, R. Gadri, P. Segur, and C. Mayoux, "Experimental and theoretical study of a glow discharge at atmospheric pressure controlled by dielectric barrier," J. Appl. Phys., vol. 83, pp. 2950–2957, Mar. 1998.

[35] Satiko Okazakit, Masuhiro Kogoma, Makoto Uehara and Yoshihisa Kimura, "Appearance of stable glow discharge in air, argon, oxygen and nitrogen at atmospheric pressure using a 50 Hz source", J. Phys. D Appl. Phys. 26 (1993) 889-892. Printed in the UK.

[36] F. Massines, N. Gherardi, N. Naudé, and P. S´egur, "Recent advances in the understanding of homogeneous dielectric barrier discharges", Eur. Phys. J. Appl. Phys. 47, 22805 (2009).

[37] Hui Jiang, Tao Shao, Cheng Zhang, Wenfeng Li, Ping Yan," Experimental Study of Q-V Lissajous Figures in Nanosecond-Pulse Surface Discharges ", IEEE Transactions on Dielectrics and Electrical Insulation Vol. 20, No. 4; August 2013.