Characteristics of argon barrier micro-discharge in various operation modes excited by a saw-tooth voltage at atmospheric pressure

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Abstract. In this work modeling of atmospheric pressure barrier discharge in argon for saw-tooth voltage signal applied to the electrodes was conducted. The model included balance equations for the densities of charged (electrons, ions) and the excited particles, the electron energy density, and the Poisson equation for the electric potential. The fluxes of charged and excited particles (electrons, ions) and electron energy were given in the drift-diffusion form. Distributions of spatiotemporal parameters of the discharge for different forms of saw-tooth voltage signal were obtained. Numerical experiments have shown that, depending on the growth rate of the external voltage, the one-dimensional model gives three forms of discharge, two of which are slightly different types of Townsend discharge, and one form is a glow discharge.

1. Introduction

In recent years, atmospheric pressure low temperature plasmas have attracted considerable attention due to their extensive applications in various fields of science and techniques. Dielectric barrier discharge (DBD) is one of the most important ways of generating low temperature plasmas with high uniformity under atmospheric pressure [1]. Atmospheric pressure uniform DBD can be divided into two categories by their breakdown mechanisms. One is the atmospheric pressure glow discharge (APGD), and the other is the atmospheric pressure Townsend discharge (APTD) [2]. APGD is characterized by the formation of a cathode fall region which is absent in APTD. The density maxima of electron and ion appear near the anode in APTD. Both APGD and APTD differ themselves greatly in properties from those of the low pressure glow or Townsend discharges. For instance, Townsend discharge is dark under low pressure, while APTD is not dark at all. Another difference is that the electron energy in APTD is higher than that in the low pressure discharge [2, 3]. Since atmospheric pressure uniform discharge has proper electron energy and is very uniform, it has extensive application potentials, such as surface modification [4], ozone generation, biological sterilization [5], pollution control [6], etc.

In some works were investigated experimentally and numerically the DBD and found an evolution process from APTD to APGD within a discharge pulse [3, 7-12]. In many works devoted to the study of discharges, a sinusoidal voltage was used. However, recently there have appeared works in which other forms of voltage were used to initiate discharges [12-16].
Therefore, it is important that investigate the discharge characteristics under various form of voltage to excitation. In this paper, the discharge properties excited by a saw-tooth for atmospheric argon DBD with a one-dimensional extended fluid model.

2. Description of the Mathematical Model

The discharge occurs between two parallel-plate electrodes covered by dielectric layers of 1mm thickness \((d_1 = d_2 = 1\, \text{mm})\). A saw-tooth voltage with amplitude 1.3kV and a repetitive frequency of 100 kHz is applied between the two electrodes. The numerical simulation is based on a one-dimensional extended fluid model [17].

The nonlinear system of partial differential equations comprises the continuity equations for particle densities, the electron energy balance equation determining the spatiotemporal evolution of the electron energy density and Poisson’s equation providing selfconsistently the electric potential and the electric field. The particle fluxes and the electron energy flux in the x-direction are given in drift-diffusion approximation [17].

To achieve an adequate description of atmospheric pressure argon plasmas, atomic and molecular argon ions \(\text{Ar}^+\), \(\text{Ar}_2^+\), and \(\text{Ar}_3^+\) as well as three effective excited atomic: metastable level \(\text{Ar}^m\), resonant level \(\text{Ar}^r\), effective excited level \(\text{Ar}^*\) and two effective excimer levels \(\text{Ar}_2^*\) and \(\text{Ar}_3^*\) were taken into account. The reaction kinetic scheme takes into account 18 electron collision processes. Besides elastic collisions contributing directly to the electron energy balance equation, it includes excitation, deexcitation, ionization and recombination processes with rate coefficients depending on the mean electron energy. In addition, 4 radiation and 16 heavy particle collision processes are considered [17].

3. Numerical simulation and results

Figure 1 shows the calculated waveforms of the electrode voltage \(V_o\), the potential drop \(V_g\) across the discharge gap, and the total DBD current density \(J_0\) for different forms of saw-tooth voltage signal (different size of transition zone between rising fronts of the applied voltage): a) for 0.1 \(\mu\text{s}\); b) 0.2 \(\mu\text{s}\; c) 0.4 \(\mu\text{s}\).

As can be seen from Fig. 1, APTD mode is observed for all three cases during the first period. On the rising front of the voltage, the conduction current gradually increases from zero to a certain value, depending on the rate of voltage growth, and then remains constant. The discharge current shows a broad plateau per part cycle corresponding on increase front of applied voltage. On a declining front, a situation is almost the same. The difference is that the discharge current consists of some pulses (damped oscillations) superimposed on the plateau.

In the second period, both on the rising and falling fronts of the supply voltage, current pulses occur corresponding to the barrier discharge of the glow type. At the same time, the rate of increase in the magnitude of the voltage on the falling edges of the voltage affects the amplitude of the current pulse. The amplitude of the current pulse is higher in the case when the value of rate of voltage growth \(dU/dt\) is greater. The periodicity of the formation of current pulses, and hence the initiation of discharges, is established in the third and fourth periods.

Fig. 2 shows the density distributions of charged (electron and sum of all ion types) and excited (sum of all types) particles, as well as the electric field strength at different times 12 mks, 26.7mks and 31.3 mks, respectively for case on fig.1 c. As can be seen at a time point of 12 mks, when current fluctuations are observed in the APTD mode, quasineutral plasma is not observed. Only the charge layers is observed. In this case, the voltage drops across the whole discharge gap. At time points of 26.7 mks and 31.3 mks, classical distributions of the discharge parameters corresponding to the APGD mode are observed.

In the case of APTD mode, a sufficiently high density of excited particles is observed in the discharge gap. The metastable argon atom \(\text{Ar}^m\) is the predominant excited particle. The predominant ions are the molecular ions \(\text{Ar}_2^+\) and \(\text{Ar}_3^+\). In the case of APGD mode, the predominant ions are also argon molecular ions \(\text{Ar}_2^+\) and \(\text{Ar}_3^+\), and the dominant excited particles are \(\text{Ar}_2^*\) and \(\text{Ar}_3^*\).
The cathode sheath is followed by the plasma region with the negative glow and Faraday dark space, where the charged particle density first increases to its maximum value near the cathode sheath and then smoothly decreases toward the anode – grounded electrode. This region is characterized by a low (inverse) field with two field reversal points.

After the second reversal point, the plasma field is gradually restored; however, as is seen from the figures, no positive column with a typical homogeneous distribution of the plasma parameters is observed. The Faraday dark space is followed by the anode sheath. The transition to the anode sheath is accompanied by the third field reversal point and the negative anode fall.

![Saw-tooth waveforms of the voltage V0 applied to the electrodes, voltage drop Vg across the discharge gap, and total current density J0 in a dielectric barrier microdischarge for different size of transition zone between rising fronts of the applied voltage)](image)

**Figure 1.** Saw-tooth waveforms of the voltage V0 applied to the electrodes, voltage drop Vg across the discharge gap, and total current density J0 in a dielectric barrier microdischarge for different size of transition zone between rising fronts of the applied voltage: a) for 0.1 μs; b) 0.2 μs; c) 0.4 μs.

In addition, a special study was conducted. When using a linearly increasing voltage, one of the parameters regulating the discharge mode is the rate of voltage growth \(dU/dt\). As a result of numerical experiments, various discharge modes were detected depending on the \(dU/dt\).

At low voltage growth rates \((dU/dt = 2 \cdot 10^8 - 3 \cdot 10^8 \text{ V/s})\), when the voltage on a discharge gap reaches a certain value, the conduction current increases smoothly from zero to a certain value, depending on the rate of voltage growth. At the same time, the voltage across the discharge gap ceases to increase, since its increase due to the growth of the external voltage is compensated by the charge transfer between the barriers. The discharge in this case is Townsend.
An increase in the value of the rate of voltage growth leads to the appearance of damped oscillations on the conductivity current profile ($dU/dt \approx 4 \cdot 10^8 - 5 \cdot 10^8 \text{V/s}$). One of the reasons for this is ion-electron emission. In addition, the current oscillations in the Townsend discharge can be due to the distortion of the electric field due to a positive space charge. In this case, they arise only in a narrow transition region between the Townsend and glow discharges and, due to this, are difficult to observe. A discharge of this type is also Townsend, since it does not observe the appearance of a quasineutral plasma and near-electrode regions.

At large values of $dU/dt$ ($dU/dt \approx 1 \cdot 10^9 \text{V/s}$), a qualitative change in the discharge behavior occurs. When the voltage across the discharge gap reaches a certain value, there is a sharp increase in current to values several orders of magnitude higher than the current in a Townsend discharge, with the voltage across the discharge gap practically falling to zero. This discharge behavior is associated with an exponential change in the field in the near-cathode region due to the space charge. Thus, depending on the growth rate of the external voltage, the one-dimensional model gives three forms of discharge, two of which are somewhat different kinds of Townsend discharge, and one form is a glow discharge. A common property for them is the Townsend breakdown mechanism, which consists in an exponential increase in the initial current at the cathode due to ionization in an electric field.

**Figure 2.** Distributions of the charged particle densities, excited particle densities, and the electric field at the different moments a) for 0.1 $\mu$s; b) 0.2 $\mu$s; c) 0.4 $\mu$s for case c on fig. 1.
4. Conclusions

Based on the one-dimensional extended fluid model, the characteristics of dielectric barrier discharge excited by saw-tooth voltage are numerically investigated in atmospheric pressure argon. Numerical experiments have shown that, depending on the rate of voltage growth, the one-dimensional model gives three forms of discharge, two of which are slightly different types of Townsend discharge, and one form is a glow discharge. Results show that the discharge mode transits from APTD to APGD when the rate of voltage growth is increase. Distributions of spatiotemporal parameters of the discharge for different forms of saw-tooth voltage signal were obtained.

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References

[1] U. Kogelschatz, B. Eliasson, and W. Egli, 1999 Pure Appl. Chem. 71 1819.
[2] F. Massines, N. Gherardi, N. Naude, and P. Segur, 2009 Eur. Phys. J.: Appl. Phys. 47 22805.
[3] F. Massines, N. Gherardi, N. Naude, and P. Segur, 2005 Plasma Phys. Controlled Fusion 47 B577.
[4] Z. Zhang, Y. Qiu, and Y. Lou, 2003 J. Phys. D: Appl. Phys. 36 2980.
[5] X. T. Deng and J. J. Shi, 2005 Appl. Phys. Lett. 87 153901.
[6] V. Y. Plaksin, O. V. Penkov, M. K. Ko, and H. J. Lee, 2010 Plasma Sci. Technol. 12 688.
[7] S. Kanazawa, M. Kogoma, and T. Moriwaki, 1988 J. Phys. D: Appl. Phys.21 838.
[8] A. Sublet, C. Ding, J. L. Dorier, C. Hollenstein, P. Fayet, and F. Coursimault, 2006 Plasma Sources Sci. Technol. 15 627.
[9] H. Y. Luo, Z. Liang, B. Lv, X. X. Wang, Z. C. Guan, and L. M. Wang, 2007 Appl. Phys. Lett. 91 221504.
[10] D. Lee, J. M. Park, S. H. Hong, and Y. Kim, 2005 IEEE Trans. Plasma Sci. 33 949.
[11] Q. Wang, J. Z. Sun, and D. Z. Wang, 2009 Phys. Plasmas 16 043503.
[12] A I Saifutdinov, A A Saifutdinova and N F Kashapov 2016 Journal of Physics: Conference Series 669 012044.
[13] N. Benard and E. Moreau, 2012 Appl. Phys. Lett. 100, 193503.
[14] A. A. Abdelaziz, T. Seto, M. Abdel-Salam, and Y. Otani, 2012 J. Phys. D 45, 115201.
[15] M. Kotsonis and S. Ghaemi, 2012 J. Phys. D 45, 045204.
[16] M. Bogaczzyk, G. B. Sretenovic, and H. E. Wagner, 2013 Eur. Phys. J. D 67, 212.
[17] A. I. Saifutdinov, A. A. Saifutdinova, and B. A. Timerkaev 2018 Plasma Physics Reports 44, 3.