PLASMA GENERATION IN THE LOW- PRESSURE GAS D.C. DISCHARGE WITH A SIMPLE EXAMPLE OF THE NOBLE GAS SYSTEM

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A new general approach, laser representations and catastrophe theory have been taken to describe plasma generation of the self- sustained gas D.C. discharge. Two regions of a self-consistent effective electrical field with qualitatively different structural properties of the positive column are found. All allows us to propose a logically self- contained classification and a description of the low- pressure steady gas D.C. discharge with the well- defined positive column for an atomic gas system and demonstrate the existence of the similarity laws for all regimes of such a discharge.

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1. INTRODUCTION

The positive column is an elementary example of a real discharge non-isothermic plasma, but until now a satisfactory theoretical description has not been available. The classical description of the positive column is given in [1-5]. *Its prediction of lack of striations, jumps, shock waves, hysteresis and other phenomena is contrary to fact, and the more so as a unit.* The catastrophe model [6] provides a good example for plasma states, jumps, and hysteresis phenomena of the discharge plasma to be described by means of a potential. How does this potential come into existence in physics and what physical processes are associated with it in the gas discharge?

It is well known that '*the processes of generation and absorption of charged particles are processes that not only determine basically the electrical properties of the positive column, but also lead to the generation of a self-sustained gas discharge by itself*' [7-9] and '*this behavior is related with an influence of the electric field on the rate of ionized reactions and the reactions impart wave nature to the behavior'* [10].

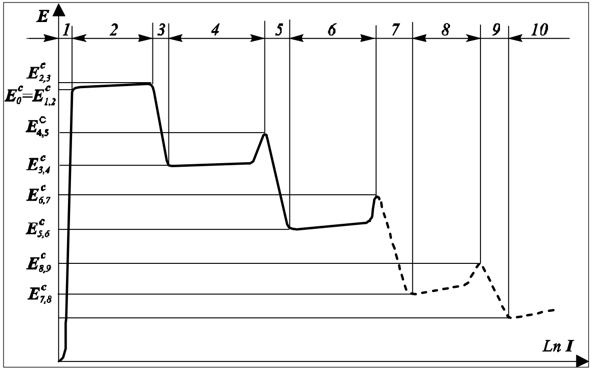

Fig. 1. The typical current- voltage characteristic

If one notices the presence of structurally similar regions at the current- voltage characteristic presented in Fig. 1 one can see that they are similar. What is mainly physical responsible for these similar laws?

The purpose of this paper is to show that the consideration of the physical processes that take place in the positive column allows one to answer all the above-mentioned questions.

We consider that it is just the positive column and that the physical processes going on in the gas discharge are an integral of it, and we can determine properties of the discharge and unambiguously characterize its type. This is illustrated by the example of an atomic gas system as ranked among the simplest and best to study. The realistic model of the given system as the Van der Vaals model of real gas and the Landau- Ginzburg model of superconductivity contains the basic properties of real gas discharge.

2. MASTER EQUATION. GENERATION AND SIMILARITY LAWS

From here on, a self- sustained gas discharge has a positive column at a gas pressure of 1-100 mm of mercury. The step processes and the volume recombination of charged particles are of primary importance in the positive column (see, for example, [1] (pp. 238, 278)). *An effort must be made to describe these processes and analyze their effect on the properties of this gas discharge.*

There are two principal but mainly different generation channels of electrons through the gas ionization, like direct and step ionizations, in the discharge. The absorption processes of charged particles, in fact they all, reduce to their own mutual charge neutralization; for example, with the assistance of a geminate dissociative or an electron- ion recombination (and other types of dissociative recombination) or a three-body electron- ion recombination in a discharge plasma. The latter process is known as the volume recombination of charged particles.

In a discharge plasma, all available experimental data (shown schematically in Fig. 1) show that the average energy of electrons is always much less than the potential of ionization of atoms in regions after the dark discharge, such as regions 3,4,5,6,7. *This fact indicates that the mechanism of step ionization always dominates over the other.* Simple estimates, for example those given in [2], confirm this assumption.

Let us derive a balance master equation for the density of electrons (and, naturally, due to the plasma quasineutrality for ions as well). Although we do not take into account the phenomena in the vicinity of electrodes, this equation allows us to explain correctly the major part of the available experimental data and, in particular, the behavior of the current- voltage characteristics. In what follows, a modification of this equation made in order to adjust it to more complete simultaneous equations provides an understanding of the emergence of striations, condition of their formation and hysteresis effect, etc. [7-9].

It should be noted that even in this case so for the arc discharge the parameter $N_e/N_a <<1$, which governs the degree of ionization, does not exceed 0.1. Here, N_a is the density of neutral atoms. Away from the electrodes, the balanced master equation for the density of electrons N_e may be written as [7, 11]:

$$\frac{\partial N_e(x,t)}{\partial t} = -\frac{\partial U(N_e,E)}{\partial N_e} + D(E)\frac{\partial^2 N_e}{\partial x^2} + F\,, \qquad (1)$$

where

$$-\frac{\partial U(N_e,E)}{\partial N_e} = K(N_e,E) = \mu + (\alpha - \alpha_0)N_e + \beta_1 N_e^2 +$$
$$+\beta_2 N_e^3 + \ldots - \gamma N_e^3 \qquad (2)$$

is the generalized force $K(N_e, E)$ associated with the potential $U(N_e,E)$, called below *a ionization potential.* The coefficients in the *ionization potential* $U(N_e,E)$ depend on the inherent self-consistent electric field E and are determined by the step ionization and other step plasma reactions. The different plasma reactions give the contributions to the coefficients $\mu, \alpha, \beta_1, \beta_2, \ldots$. These quantities are found by averaging over a plasma ensemble. One can see that the structure of this potential corresponds to the phenomenological potential of type introduced in [6] to explain of the hysteresis phenomena in a gas discharge. The ionization potential binds the processes of generation and absorption of electrons together. *It has been just these processes, which have lead to the form of the potential as being used for description of the basic properties of the gas discharge plasma system as a unit.* Here, we mean that the *local* quasineutrality condition $N_e \approx N_i$ takes place in the positive column, where the step processes are essential and the master equations are averaged over the typical spatial size of the order of Debye radius r_d, i.e. the given grain size is considered as a point. Here, for simplicity we consider that $D(E)$ is the ambipolar diffusion coefficient, which does not depend on the electric field.

Equation (1) may be cited as *a typical representative of diffusion – plasma chemical reaction equations and Langevin equations also* [7, 11, 12]. Similar Langevin equations form a basis for the superconductivity theory (The Landau-Ginzburg equation), laser, etc. [13]. *A distinctive feature of our approach is that we have refined the mechanisms of electron ionization and absorption and have dropped the ambipolar diffusion term and the fluctuating force F for the present.*

Extremes of the ionization potential $U(N_e,E)$, namely, the condition

$$\frac{\partial U(N_e,E)}{\partial N_e} = -K(N_e,E) = 0\,, \qquad (3)$$

define plasma states of gas discharges. By transformations of a shift, an expansion etc., the condition can be put in a given initial canonical form

$$\frac{\partial U\big(N_e', p(E), q(E)\big)}{\partial N_e'} = N_e'^3 + p(E)N_e' + q(E) = 0\,. \qquad (4)$$

Taking to zero the derivative of the ionization potential $U(N_e, p, q)$ (4) with respect N_e can be conceived of as a surface, $p(E)$ and $q(E)$ being coordinates in a generalized three- dimensional (N_e, p, q) space in which the structure of the potential to be reduced to a canonical form after Thom [14]. The surface called as the *ionization equilibrium surface* is a universal form called the ‘wrinkle’. The projection of the surface on the (p, q) plane is shown on Fig. 2. The properties of physical systems, whose ionization equilibrium surfaces are described by equations (3) and (4), are similar to each other, as *these transformations do not change the topology of surfaces.* The similarity laws for types of such a discharge are a result of this fact.

All functions parameterized by control parameters from range I (see Fig. 2) have a unique minimum. All functions of the considered form parameterized by points of range III should have the two local minima and only the one local maximum.

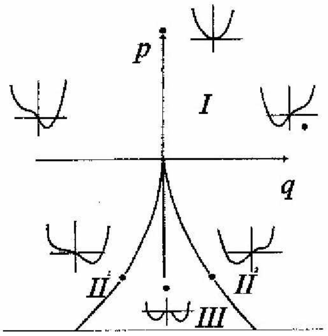

Fig. 2. The projection of the surface on the (p, q) plane There are paths (p, q) corresponding to its V-A characteristic and its local ionization potential $U(N_e, p, q)$ for any one of gases in the gas discharge. Every this path has a behavior of a given physical system

The physical system deals with *the terminal group* of the behavior despite the fact that it moves over the equilibrium surface along a path of complex shapes. From this consideration of the ‘static’ properties of the potential $U(N_e, p, q)$ it follows that the qualitative behavior of the plasma system depends on the parameters $(p,q) = (p(E), q(E))$. Range I and regions with even numbering (2, 4, 6…) in the current- voltage characteristic [7] can be said with certainty to correspond to solutions with spatial homogeneity of a certain type of the self- sustained discharge. Range III and regions with odd numbering (1,3,5) correspond to the transition zones between adjacent types of self- sustained discharge [8,9]. Over these regions of physical parameters, the plasma system takes place in either the discharge mode with the appearance of jumps, hysteresis and stratified phenomena. There are sheets (floors) of states with various densities of electrons and ions in gas discharges, and the transition regions are interconnected ‘escalators’.

Let us analyze the stationary solutions of equation (4) in order of increasing ionization parameter N_e/N_a. The discharge shown in Fig.1 in region 1 of the current-voltage characteristic can be determined from the linear approximation of equation (1):

$$N_{e1} \cong -\mu/(\alpha - \alpha_0). \qquad (5)$$

If the direct contribution of the coefficient α can be neglected $(\alpha \approx 0)$ due to the threshold dependence on the electrical field E, equation (5) takes the following form:

$$N_{e1} \cong \mu / \alpha_0. \qquad (6)$$

A breakdown occurs as the field E reaches its threshold or critical value $E = E_0^C = E_{1,2}^C$. Expression (5) becomes infinite at this point. It shows that it is necessary to take into account the saturation effects in electron multiplication. The two-particle electron-ion dissociative recombination is mainly responsible for the electron losses at the stage of the Townsend (shaping dark) discharge [1-5], saturation being determined by a nonlinearity that is quadratic on N_e.

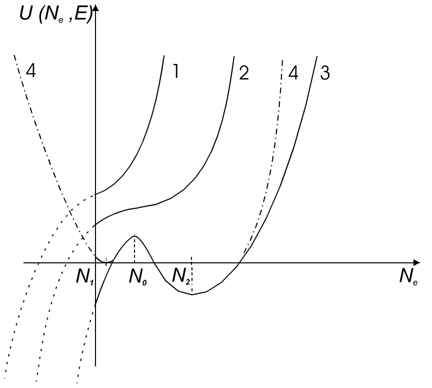

Fig. 3. The modification of the ionization potential U (Ne,, E) in close vicinity to the point of breakdown

Fig. 2 a show modifications of the ionization potential *U (Ne,, E)* versus the strength of the (self-consistent) electrical field *E*. The structures of transitions at critical points are identical.

The physically inaccessible range, negative in N_e, in the ionization potential *U (Ne,, E)* is isolated. It is shown by a dashed line. These two minima, namely the usual and the conditional, will be realized as two stationary stable solutions of equation (3) in this approximation. The conventional minimum of the ionization potential in the neighborhood of zero is actually displaced and determined by approximate formula (6) obtained earlier. The stable solution is associated with the usual minimum of the ionization potential *U (Ne,, E)* and corresponds to the self- sustained mode, called the dark or Townsend discharge. The densities of electrons and the current within region 2 are determined by the formula

$$N_{e2} \cong -\frac{\alpha-\alpha_0}{2\beta_1}+\sqrt{-\frac{\mu}{\beta_1}+\left(\frac{\alpha-\alpha_0}{2\beta_1}\right)^2}. \qquad (7)$$

The transition from the non-self- sustained (chaotic) mode to the self- sustained mode of the gas discharge takes place in the vicinity of the critical point $E_0^C = E_{1,2}^C$ and is associated with the Townsend breakdown. This transition can be qualitatively distinguished. The transition zone under study is *an isolated point* and is separated from other transition zones corresponding to *the finite interval* of the electric field between other types of the self- sustained gas discharge. In the latter case, stratified or hysteresis phenomena are observed.

Thus, the first self-consistent state, named the dark or Townsend discharge, has the density of electrons (and 'ionic skeleton') (7). The existence of falling region 3 in Fig. 1, when passing from the dark (Townsend) discharge (2) to the glow one (4), suggests that it is necessary to take into account the next expansion terms in equation (4) down to the third degree on N_e. The mechanisms providing the effects of saturation of the following order are directly connected with volume recombination.

Region 4 of the current- voltage characteristic is in agreement with the self- sustained mode called a glow discharge. Here, the coefficient β_1 met with in $\beta_1 N_e^2$ has the sign opposite (plus) to that in the case discussed above (namely, for the quadratic-law mechanism of saturation, where this coefficient has the minus sign). It is mainly determined by step ionization. The stationary solutions of equation (4) in this approximation are found from the expression [15]

$$N_{e4}=\sqrt[3]{-\frac{q}{2}+\sqrt{\left(\frac{p}{3}\right)^3+\left(\frac{q}{2}\right)^2}}+\sqrt[3]{-\frac{q}{2}-\sqrt{\left(\frac{p}{3}\right)^3+\left(\frac{q}{2}\right)^2}}, \qquad (8)$$

where

$$q=q(E)=-\left[2\left(\frac{\beta_1}{3\gamma}\right)^3+\frac{\beta_1(\alpha-\alpha_0)}{3\gamma^2}+\frac{\mu}{\gamma}\right]$$

$$p=p(E)=-\left[\frac{1}{3}\left(\frac{\beta_1}{\gamma}\right)^2+\frac{\alpha-\alpha_0}{\gamma}\right]. \qquad (9)$$

Region 6 of the current- voltage characteristic is in agreement with the self- sustained mode called an arc discharge. The density of electrons (ions) is given by similar formula (8) provided that

$$q=q(E)=-\left[2\left(\frac{\beta_1}{3(\gamma-\beta_2)}\right)^3+\frac{\beta_1(\alpha-\alpha_0)}{3(\gamma-\beta_2)^2}+\frac{\mu}{\gamma-\beta_2}\right]$$

$$p=p(E)=-\left[\frac{1}{3}\left(\frac{\beta_1}{\gamma-\beta_2}\right)^2+\frac{\alpha-\alpha_0}{\gamma-\beta_2}\right]. \qquad (10)$$

In upper hardly rising region 4, where $p = p(E) > 0$, the possibilities for the existence of a multiplication channel through the metastable excited atoms have reached a certain limit, and the competition between the direct and stepwise processes is beginning again. The mode states of the discharge corresponding to falling regions 3 and 5 are unstable from stratification. We do not consider transition region 5 for the same reason, and come to region 6 of the current- voltage characteristic, which is called the arc discharge or the electrical arc. Here, the multiplication process of electrons takes place through the metastable state of singly charged ions or ionic complexes, and the main mass of ions becomes double ionized at the end of region 6. Experimental data [1] correspond to sharp rise region 6. They indicated the limit of the possibilities of saturation of electron multiplication by stepwise processes through singly charged ions in the discharge characteristic. In region 6 of this characteristic, the rise of the discharge characteristic is the same as that of region 4. The falling (transition) region 7 and subsequent regions 8, 9, 10 ... have not yet been observed experimentally. It seems that the following stages of stripping are possible, and there should be other types of self- sustained discharge.

Thus, the physical basis of the similarity between the properties of the regions of current- voltage characteristic represented in Fig. 1 is a replacement of one type of stepwise processes, $A^{*} + e \rightarrow A^{+} + 2e$, by another related stepwise process, $A^{+*} + e \rightarrow A^{++} + 2e$. Here, A^{*}, A^{+*} are the metastable excited atoms and the singly charged atoms, respectively, and A^{+}, A^{++} are the remaining states of singly and double charged ions. *These plasma reactions are analogous to some chemical ones* [12, 13]; *for example, Belousov-Zhabotisky reactions (see references in* [13]) *in which, under homogeneous conditions, there were periodic spatio-temporal structures analogous in conception to such phenomena as striations. What this means that Pekarec's prediction* [10] *has been justified.*

3. CONCLUSIONS

It is clear that analysis of the balance control equation (1) can be complicated by the inclusion of ambipolar diffusion, the electron affinity electron, etc. The previous classification, however, will remain and can be applied to gas discharges in the pressure range where stepwise processes are essential. In our opinion, this method for attacking the problem of plasma generation gives a clue to the understanding of the nature of globe lighting.

The introduction of a general potential provides a basis understanding of the general concept of the phenomena in gas discharges. The potential gives an insight as Townsend, glow and arc types (or modes) of the gas discharge and relations in between are closely associated with plasma reactions. Analysis of plasma system dynamics with the potential offers a clearer view of how the phenomena in the gas discharge as a unit come into being.

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ГЕНЕРАЦИЯ ПЛАЗМЫ В ГАЗОВОМ РАЗРЯДЕ, ВОЗБУЖДАЕМОМ ПОСТОЯННЫМ ТОКОМ, НА ПРОСТОМ ПРИМЕРЕ СИСТЕМЫ ИЗ БЛАГОРОДНОГО ГАЗА

П.Ф. Курбатов

Новый обобщенный метод, лазерные представления и теория катастроф были использованы для описания генерации плазмы самостоятельного газового разряда, возбуждаемого постоянным током. Обнаружены два вида областей самосогласованного эффективного электрического поля с качественно различными структурными свойствами положительного столба. Все это позволяет предложить логически самосогласованную классификацию и описание стационарного газового разряда постоянного тока с хорошо определенным положительным столбом для атомарной газовой системы и продемонстрировать существование законов подобия всех режимов такого разряда.

ГЕНЕРАЦІЯ ПЛАЗМИ В ГАЗОВОМУ РОЗРЯДІ, ЩО ЗБУДЖУЄТЬСЯ ПОСТІЙНИМ СТРУМОМ, НА ПРОСТОМУ ПРИКЛАДІ СИСТЕМИ ІЗ БЛАГОРОДНОГО ГАЗА

П.Ф. Курбатов

Новий узагальнений метод, лазерні зображення і теорія катастроф були використані для опису генерації плазми самостійного газового розряду, що збуджується постійним струмом. Виявлено два види областей самоузгодженого ефективного електричного поля з якісно різними структурними властивостями позитивного стовпа. Усе це дозволяє запропонувати логічно самоузгоджену класифікацію й опис стаціонарного газового розряду постійного струму з добре визначеним позитивним стовпом для атомарної газової системи і продемонструвати існування законів подібності всіх режимів такого розряду.