ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)

ҚАЗАҚСТАН РЕСПУБЛИКАСЫ
ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫНЫҢ

ХАБАРЛАРЫ

ИЗВЕСТИЯ

НАЦИОНАЛЬНОЙ АКАДЕМИИ НАУК
РЕСПУБЛИКИ КАЗАХСТАН

NEWS

OF THE ACADEMY OF SCIENCES
OF THE REPUBLIC OF KAZAKHSTAN

ГЕОЛОГИЯ ЖӘНЕ ТЕХНИКАЛЫҚ ҒЫЛЫМДАР СЕРИЯСЫ

◆

СЕРИЯ ГЕОЛОГИИ И ТЕХНИЧЕСКИХ НАУК

◆

SERIES OF GEOLOGY AND TECHNICAL SCIENCES

1 (421)

ҚАҢТАР – АҚПАН 2017 ж.
ЯНВАРЬ – ФЕВРАЛЬ 2017 г.
JANUARY – FEBRUARY 2017

ЖУРНАЛ 1940 ЖЫЛДАН ШЫҒА БАСТАҒАН
ЖУРНАЛ ИЗДАЕТСЯ С 1940 г.
THE JOURNAL WAS FOUNDED IN 1940.

ЖЫЛЫНА 6 РЕТ ШЫҒАДЫ
ВЫХОДИТ 6 РАЗ В ГОД
PUBLISHED 6 TIMES A YEAR

АЛМАТЫ, ҚР ҰҒА
АЛМАТЫ, НАН РК
ALMATY, NAS RK

«ҚР ҰҒА Хабарлары. Геология мен техникалық ғылымдар сериясы».
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)
Меншіктенуші: «Қазақстан Республикасының Ұлттық ғылым академиясы» РҚБ (Алматы қ.).
Қазақстан республикасының Мәдениет пен ақпарат министрлігінің Ақпарат және мұрағат комитетінде 30.04.2010 ж. берілген **№10892-Ж** мерзімдік басылым тіркеуіне қойылу туралы куәлік.

Мерзімділігі: жылына 6 рет.
Тиражы: 300 дана.

Редакцияның мекенжайы: 050010, Алматы қ., Шевченко көш., 28, 219 бөл., 220, тел.: 272-13-19, 272-13-18, http://nauka-nanrk.kz /geology-technical.kz

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Редакцияның мекенжайы: Қазақстан, 050010, Алматы қ., Қабанбай батыра көш., 69а.
Қ. И. Сәтбаев атындағы геология ғылымдар институты, 334 бөлме. Тел.: 291-59-38.

Типографияның мекенжайы: «Аруна» ЖК, Алматы қ., Муратбаева көш., 75.

«Известия НАН РК. Серия геологии и технических наук».
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)
Собственник: Республиканское общественное объединение «Национальная академия наук Республики Казахстан (г. Алматы)
Свидетельство о постановке на учет периодического печатного издания в Комитете информации и архивов Министерства культуры и информации Республики Казахстан **№10892-Ж,** выданное 30.04.2010 г.

Периодичность: 6 раз в год
Тираж: 300 экземпляров

Адрес редакции: 050010, г. Алматы, ул. Шевченко, 28, ком. 219, 220, тел.: 272-13-19, 272-13-18,
http://nauka-nanrk.kz /geology-technical.kz

Адрес редакции: Казахстан, 050010, г. Алматы, ул. Кабанбай батыра, 69а.
Институт геологических наук им. К. И. Сатпаева, комната 334. Тел.: 291-59-38.

Адрес типографии: ИП «Аруна», г. Алматы, ул. Муратбаева, 75

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News of the National Academy of Sciences of the Republic of Kazakhstan. Series of geology and technology sciences.
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)
Owner: RPA "National Academy of Sciences of the Republic of Kazakhstan" (Almaty)
The certificate of registration of a periodic printed publication in the Committee of information and archives of the Ministry of culture and information of the Republic of Kazakhstan N 10892-Ж, issued 30.04.2010

Periodicity: 6 times a year
Circulation: 300 copies

Editorial address: 28, Shevchenko str., of. 219, 220, Almaty, 050010, tel. 272-13-19, 272-13-18,
http://nauka-nanrk.kz/geology-technical.kz

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Editorial address: Institute of Geological Sciences named after K.I. Satpayev
69a, Kabanbai batyr str., of. 334, Almaty, 050010, Kazakhstan, tel.: 291-59-38.

Address of printing house: ST "Aruna", 75, Muratbayev str, Almaty

N E W S
OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC OF KAZAKHSTAN
SERIES OF GEOLOGY AND TECHNICAL SCIENCES
ISSN 2224-5278
Volume 1, Number 421 (2017), 197 – 204

UDC 537. 523.3:541.13

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MODELING OF PROCESSES IN THE ZONE OF CORONA DISCHARGE IONIZATION

Abstract. The article presents a system of differential equations, modeling the processes in the area of corona ionization. On the basis of its analytical solutions there obtained analytical dependencies of ions and electrons density, in accordance with their diffusion, on the field strength in the corona layer, that is, in the corona hood. There presented the corona hood structure, as well as the diagram of the elementary processes in it. Automated installation for air ozonation indoor agriculture is presented. It is given a description of the executable functions and processes, component parts and system components. In the technical description of the automatic frequency control unit shows the electronic and controls. The paper shows and describes structure and flowchart automatic control unit ozone concentration in the working volume. It is shown a real possibility of automation control and monitoring of ozone concentrations in the application ozonometers installed around the perimeter of the working volume.Development of high-tech ozone and ozonated devices is of great importance and requires the study of theoretical positions and analysis of experimental data, the totality of which would allow to develop scientifically sound methodological design of these systems device with reference to the requirements of food industry. The present work is the first attempt to study the theory and methodology of research of physical and chemical processes in the negative ozonation crown with the MP in the air. The results of the mechanism and kinetics of ozone electrosynthesis research in this type of discharge allowed to create preconditions for the development of new guidelines on ozone corona discharge with a high energy efficiency and ozone productivity. Systematization of data on the applications of ozone in different sectors of industry, medicine and agriculture, significantly expand the scope of application of ozone technology in general.

Keywords: air ozonation, ozone concentration, frequency control, automatic installation for air ozonation, monopolar corona, Townsend coefficients, ions, electrons, diffusion, densities, corona hood.

1. Introduction. Corona discharge appears in gaseous medium upon sufficient voltage supply to electrodes. At that, discharge electrode is made in the form of thin wire, which allows to create ionization zone on it. As a rule, negative potential is supplied to a corona electrode. Electrons from ionization zone while moving to the anode, attach to neutral atoms and gas molecules, forming negative ions. Those ions, influenced by an electric field in the external area of corona discharge upon moving to the anode, create discharge current [1].

Many developments of electronic-ion technologies (electric gas purification, electric separation, dust suppression, electrocoating) [2] and ozone electrosynthesis installations are based on corona discharge [3]. In the most cases, corona discharge is used in atmospheric air at pressures close to normal.

In the recent time there were developed small-sized ozonizers and ozone measurement devices on the base of corona discharge, which following advantages compared to the known ones: simple design and small size, slight impact of pressure and speed of passing air at their characteristics, ecological safety and no need in air handling [4]. Monopolar corona discharge serves as ozonizing element in those ozonizers at small inter-electrode gaps (5-10 mm), and discharge electrode is a micro electrode in the form of a needle, microwire (10-100 microns) or thin spiral.

A number of experimental studies of monopolar corona in the electrode cylindrical system, for example, measuring the mobility of ions in the outer area, HF diagnosis of corona ionization zone, etc., showed that the discharge layer or corona hood is the key, determining the characteristic features of the discharge in general [4]. Ionization corona discharge processes (ionization, excitation, recombination, diffusion, electron attachment, etc.) occur primarily in the corona hood close to the discharge electrode with a small radius of curvature.

In this regard, the task is: the mathematical description of the corona hood structure and processes modeling in the zone of ionization through solution of a differential equations system with account of ions and electrons diffusion

2. Training of parameters. Our work [5] presents theoretical formulation and analysis of one-dimensional model of gas flow (liquid) with a needle electrode. Also there developed a two-dimensional mathematical model of the corona discharge as a function of gas medium parameters, supply voltage and design parameters of corona discharge gap [6].

It should be noted, that in the papers [5-6] the contribution of diffusion current, which occurs due to high densities of ions and electrons in the corona hood is not taken into consideration. In addition, the outer boundary of the discharge zone was not clearly defined, and in both cases it is delineated with a parabola or paraboloid, passing through the coordinate origin (discharge electrode) and the edge of the outer electrode. In this case, despite the great convenience of calculation models, the space of development and discharge processes of propagation is deliberately limited.

The most favorable for the study of a monopolar corona discharge is the shape of the electrodes in the form of axially symmetric cylinder, where the discharge electrode serves as microwire, and external electrode - metal cylinder covered on both sides by security similarly shaped electrodes to avoid edge effects of the electrostatic field measuring electrode. Length measuring electrode L = 1 cm, its diameter can vary from 10 to 20 mm, and the diameter of a microwire - from 10 to 100 microns.

The corona hood structure includes the distribution of space charges concentration along hood thickness and their natural composition, distribution of the field intensity and the potential in corona layer, at that, the discharge process physics will essentially depend on the polarity of the dicharge electrode. For the first time the effect of space charge at the field strength in the corona was qualitatively considered by Rogowski [7] and later, proceeding from Townsend-Rogowski theory of electron avalanches, quantitative calculation was made by N.A. Kaptsov [1]. Due to the lack of experimental studies on the properties of the corona layer, the mechanism of elementary processes in corona hood and their effect at a particular characteristic of a monopolar corona is still unclear. Meanwhile, to determine the distribution of E and ρ in the corona layer, while there might exist their high gradients, it is necessary to consider the ions and electrons transport processes in view of their diffusion. This task, excluding the diffusion process was consistently solved by Kaptsov [1]. Here is the solution for negative corona, when the diffusion of negative and positive ions and electrons is taken into consideration..

The dynamics of the processes in the corona layer can be described by the following equations:

$$divE = \frac{\rho}{\varepsilon_0} = \frac{\rho_+ - \rho_- - \rho_e}{\varepsilon_0}; \qquad (1)$$

$$j = (k_+\rho_+ + k_-\rho_- + k_e\rho_e)E - D_+\nabla\rho_+ - D_-\nabla\rho_- - D_e\nabla\rho_e;$$

$$divj = 0 = k_+\rho_+ divE + Ek_+ grad\rho_+ + k_-\rho_- divE + Ek_- grad\rho_- + k_e\rho_e divE +$$
$$+ Ek_e grad\rho_e + D_+\nabla\rho_+ - D_-\nabla\rho_- - D_e\nabla\rho_e;$$

$$j = j_+ + j_- + j_e,$$

where j_+, j_-, j_e – current densities, attributable to the share of each kind of charged particles; ρ_+, ρ_-, ρ_e densities of space charges.

If you know the total space charge density ρ, then the substitution of it into (1) and its solution with respect to E gives us the distribution of the field strength in the corona layer.

If the current density of electrons, emerging out of the surface of the corona wire is designated as j1, then using the second Townsend coefficient, we obtain

$$j_1 = \gamma j_+ = \gamma(j - j_1), \tag{2}$$

$$j_1 = j\frac{\gamma}{1+\gamma}, \tag{3}$$

where it is accepted at $\gamma = \gamma_0$, $j = j_e + j_+$, $j_- = 0$.

When taking into account not only the electron current je, but the share of current, carried by negative ions, the law of increase of avalanches can be written as follows:

$$j_- + j_e = j_1 \exp(\int_{r_0}^{r} \alpha dr) = j\frac{\gamma}{1+\gamma}\exp(\int_{r_0}^{r} \alpha dr). \tag{4}$$

With the development of electron avalanches from the corona wire the formation of negative ions begins somewhere inside the corona layer at a distance r_n from the wire axis at a given field strength En. With further advancement of electron avalanches, number of negative ions will increase. If we denote by b the ratio of the current density of negative ions to the total current falling to the share of all negative charge carriers, we can write

$$b = \frac{j}{j_- + j_e}, \tag{5}$$

$$j = b(j_- + j_e) = j\frac{\gamma}{1+\gamma} b\exp(\int_{r_0}^{r} \alpha dr), \tag{6}$$

where it is accepted at $r < r_n$, $b = 0$; at $r > r_n$, $b = 1$.

For electric current intensity of the individual components of the charged particles we have:

$$I_+ = 2\pi r j_+ = 2\pi r k_+ \rho_+ E - 2\pi r D_+ \nabla\rho_+,$$

$$I_- = 2\pi r j_- = 2\pi r k_- \rho_- E - 2\pi r D_- \nabla\rho_-,$$

$$I_e = 2\pi r j_e = 2\pi r k_e \rho_e E - 2\pi r D_e \nabla\rho_e,$$

the sum of which is the full force of the current to the corona wire length unit

$$I = I_+ + I_- + I_e.$$

And it is composed in the outer area of the corona layer of the positive ions' power current I +, of negative ions' power current I_- and electron power current I_e. Using the ratios (2-6) we can obtain

$$I_+ = I - I\frac{\gamma}{1+\gamma}\exp(\int_{r_0}^{r} \alpha dr),$$

$$I_- = I\frac{\gamma}{1+\gamma} b\exp(\int_{r_0}^{r} \alpha dr),$$

$$I_e = (1-b)I\frac{\gamma}{1+\gamma}\exp(\int_{r_0}^{r} \alpha dr),$$

then for the distribution of space charges in the corona layer, we obtain the following linear differential equations:

$$\rho'_+ - \frac{k_+}{D_+}E\rho_+ + \frac{I}{2\pi r D_+}\left[1 - \frac{\gamma}{1+\gamma}\exp(\int_{r_0}^{r} \alpha dr)\right] = 0, \tag{7}$$

$$\rho'_- - \frac{k_-}{D_-}E\rho_- + \frac{I}{2\pi r D_-}\cdot\frac{\gamma}{1+\gamma} b\exp(\int_{r_0}^{r} \alpha dr) = 0, \tag{8}$$

$$\rho_e' - \frac{k_e}{D_e}E\rho_e\frac{I}{2\pi r D_e}\cdot\frac{\gamma(1-b)}{1+\gamma}\exp(\int_{r_0}^{r}\alpha dr) = 0. \tag{9}$$

For writing's simplication in the solution of equations (7-9), we introduce the following notations

$$a_+ = \frac{k_+}{D_+},\quad a_- = \frac{k_-}{D_-},\quad a_e = \frac{k_e}{D_e},\quad E = -\frac{d\varphi}{dr},\quad \frac{\gamma}{1+\gamma} = A,\quad \int_{r_0}^{r} adr = \ln\frac{\gamma}{1+\gamma} = \ln A,$$

and taking into account the boundary conditions (r = r$_0$), where the integration constants are zero, the solutions of these equations will be more demonstrative [4]:

$$\rho_+ = \frac{I}{2\pi D_+}(Ae^{\ln A} - 1)e^{\alpha_+(\varphi-\varphi_0)}\int_{r_0}^{r} e^{-\alpha_+(\varphi-\varphi_0)}\frac{dr}{r}, \tag{10}$$

$$\rho_- = \frac{-IbA}{2\pi D_-}e^{\ln A+\alpha_-(\varphi-\varphi_0)}\int_{r_0}^{r} e^{-\alpha_-(\varphi-\varphi_0)}\frac{dr}{r}, \tag{11}$$

$$\rho_e = -\frac{I(1-b)A}{2\pi D_e}e^{\ln A+\alpha_e(\varphi-\varphi_0)}\int_{r_0}^{r} e^{-\alpha_e(\varphi-\varphi_0)}\frac{dr}{r}. \tag{12}$$

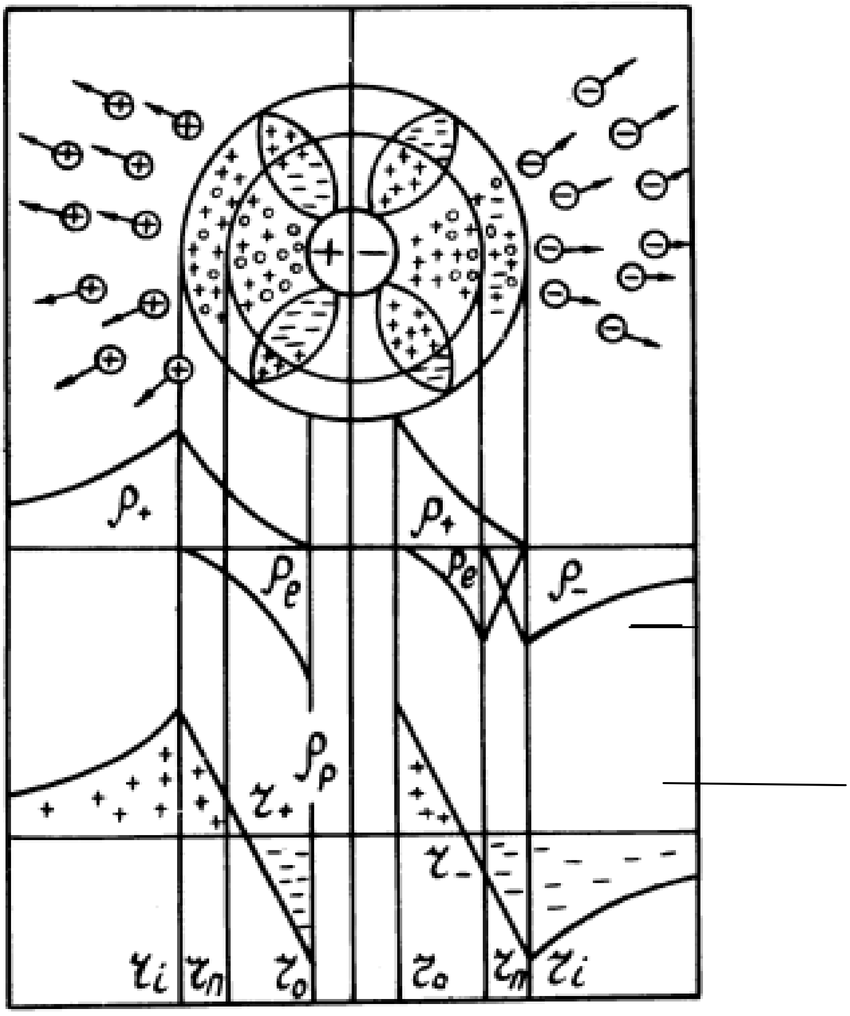
The total volume charge ρ , derived from these data will allow, by substituting it in the equation (1), determining the distribution of the field and potential intensity in corona layer. It should be noted, that the solution of differential equations of monopolar corona field becomes much more complicated, when taking into account the diffusion of ions and electrons. Determination of space charges density according to the formulas (10-12), in the main, solves the problem of ions and electrons concentration distribution in the corona layer. Their analysis shows, that the distribution ρ_+, ρ_-, ρ_e along the radius are exponential. If the value ρ_+ drops gradually to the outer area, reaching zero at r = ri, then the density of the negative ions space charge will increase, starting at zero at r ≥ r$_n$, to a maximum at r = r$_i$. The electron density increases to a maximum, when the radius comes to r$_n$, and with the formation of negative ions r ≥ r$_n$, it drops to a minimum.

The equations of the ions and electrons density of monopolar corona, considering diffusion, though complement the charge elementary mechanism and is useful for describing processes in it, do not give a clear answer about the distribution of the field and potential strength in the corona hood. In addition, based on the received data, we cannot unambiguously derive expressions for determining the current-voltage characteristics of the discharge, the initial field strength and other parameters of a monopolar corona. Thus, at the negative corona negative ions begin intensely formed in the area (r$_i$-r$_n$) and further move to the outer region of the corona discharge. With a positive corona the negative ions, formed as a result of attaching free electrons to neutral molecules and atoms, at the approach to the border of the inner area (r$_n$), are destroyed and supply free electrons to support avalanche process in corona hood. If we take as a basis the fact, that all negative ions are destroyed at E ≥35-40kV / cm, it is necessary to assume the existence of corona layer area (r$_n$-r$_0$), where there are no negative ions, regardless of the discharge electrode polarity. Meanwhile, there is no reason to believe, that the transition from the field (r$_n$-r$_0$) to (r$_i$-r$_n$) takes place very rapidly, on the contrary, it must be assumed, that the border is more or less vague, and the formation and decay of negative ions start already when approaching r$_n$ boundary from one or another side.

On the basis of equations analysis (10-12) and the experimental data there obtained a qualitative picture of the hood structure of the corona and set the distribution of ions and electrons in the discharge layer for both polarities of monopolar corona (Figure 1). The figure shows the development of the individual electron avalanches in the hood of positive and negative coronas, and the electrons are indicated by small circles.

At stationary monopolar corona due to overlapping and overriding of a large number of simultaneously occurring electron avalanches in the corona layer, there is set a dynamic equilibrium of ions and electrons density distribution, i.e., each point of discharge gap has certain values ρ_+, ρ_-, ρ_e.

The positive corona is most simple in the description: due to increased intensity of ionization processes and the effect of the electrode geometry (cylindrical system), flow of electrons has a maximum density near the surface of the corona wire, while the density in the positive ions increases gradually as it approaches the outer portion of the corona hood. Their concentration reaches a maximum at a distance (r_i-r_0) from the surface of the wire, and then decreases slowly to the outer electrode. Due to the insignificant ρ - in the area of (r_i-r_n), the distribution of negative ions is not shown in the picture:



Density distribution of positive (ρ_+) and negative (ρ_-) ions, electrons (ρ_e) and resultant space charge (ρ_p)

Figure 1 – Structure of monopolar corona hood

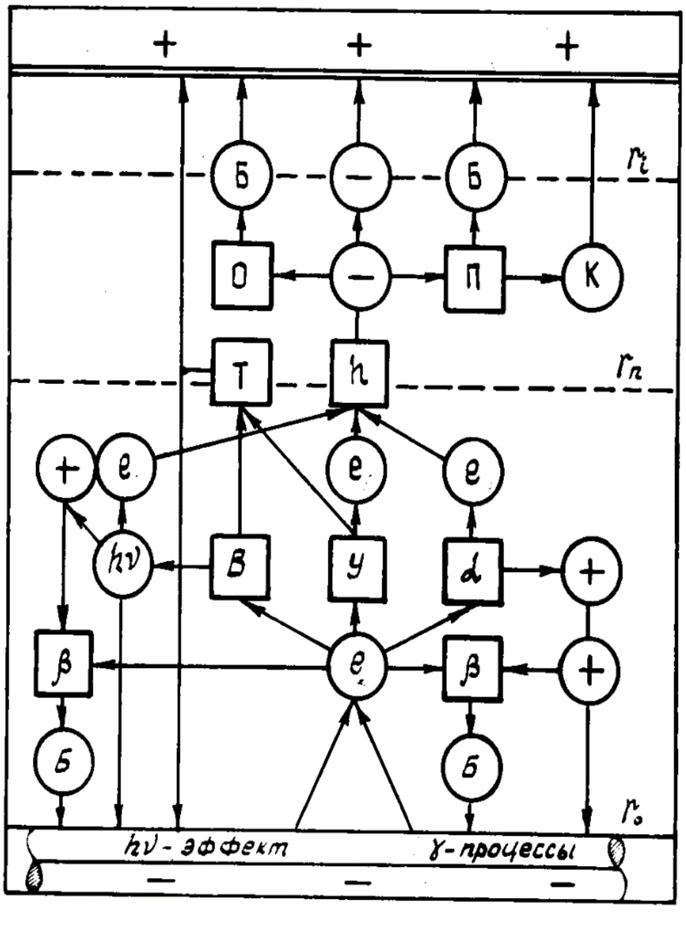
At negative corona the electron density is maximum only at the inner portion boundary r_n,, because in further in the area of (r_i-r_n) there started formation of negative ions, which are the current carriers in the outer area of the discharge. If in either case, in the field of (r_n-r_0) there observed electron-ion recombination processes, then at negative corona in the outer area (r_i-r_n) they can be supplemented with other elementary processes: electrons attachment and detachment, ionic charge exchange, etc.

Proceeding from the analysis of the curves of the resultant space charge ρ_p, the following conclusions can be drawn. In the corona layer there are high gradients of charged particles of either polarity. In addition, there are areas (r +, r-), where $\rho_p = 0$, inside the corona hood. This means that the field strength at these points is equal to the electrostatic one ($E_э$), i.e. E_p curve should intersect with $E_э$, particularly at those points (r_+, r_-). Positive space charge (ρ_+) in the negative electrode increases the field strength, speeding up the process of positive charges attraction to the wire. In case of positive corona, electron avalanches move towards the discharge electrode, leaving a cloud of positive ions behind, which are slowly coming out of the ionization zone into the inter-electrode space. The space charge, generated by positive ions, so to speak, screens off the ionization zone from the outer electrode field, which leads to a decrease of the discharge electrode field strength and to its marked increase in the external space [4].

To determine the thickness of the corona layer you can also use the Pike formula [4]. Under normal atmospheric conditions (δ = 1) it shows, that upon the ignition of the corona discharge, the electric field intensity at a distance Δ = 0,308 $\sqrt{\ }$ r_0 from the discharge electrode, remains constant for any r_0 and equal to 31kV / cm [4]. Neglecting the influence of space charge in the discharge layer ($E_0 \cdot r_0 = E_r$), we obtain

$$\Delta = \frac{E_0 r_0}{E_i} - r_0 = \frac{E_i\left(1 + \frac{0{,}308}{\sqrt{r_0}}\right) r_0}{E_i} - r_0 = 0{,}3\sqrt{r_0}, \qquad (13)$$

indicating a layer thickness independence on the discharge current intensity. Apparently, the formula (13) is valid only when the condition $E_0 r_0 = E_r$ is performed. Calculations by Kaptsov's method [1] and the formula (13) show, that the values Δ of the formula (13) is approximately three times less than its value obtained in the work [1]. This is primarily explained by the low values of E_i = 15,2kV / cm, adopted in the work [1] for calculating the thickness of the corona layer.



arrows indicate processes or transitions,
squares - the types of elementary processes,
circles – formed particles

Figure 2 – Diagram of elementary processes in corona hood

It should be noted, that the more complicated is the description of the outer portion (r_i-r_n) of the negative corona hood, where, along with the considered elementary processes there additionally exist electron attachment and detachment processes. In this case, keeping the formation and decay of negative ions leads to further complication of differential equations solution of the corona [4]. Schematic diagram of various elementary processes occurring in the corona layer of the negative corona (r_i-r_0) is shown in Figure 2.

The complexity of the processes nature in the discharge layer must be attributed not to the elementary processes in themselves, but to possible occurrence of a large variety of processes (Figure 2).

In the inner portion of the corona layer (r_n-r_0) free electrons (e), colliding with atoms and molecules of the gas, lead to a number of different processes, such as elastic collisions (y) ionization (α), agitation (B) and, if they clashe with the newly formed positive ions, to recombination (β). Simultaneously with these processes there occurs radiation (hν), appear excited atoms and ions, and on the surface of the negative electrode there take place γ- processes and photoelectric emission (h ν). Positive ions can knock out electrons from the cathode and, moving to the discharge electrode, form fast neutral atoms (Б) upon recombination with electrons.

Negative ions appear in the (r_i-r_n) area, where there are processes of electron attachment (h) to neutral gas atoms. In this area, due to ion exchange processes (П) and the detachment of electrons (O) there also exist complex ions (K) and fast atoms (Б).

It should be noted, that the corona discharge, as at other forms of gas discharge, generates heat (T): part of the electrons energy, ions and fast molecules or atoms will be manifested in the heating of gas and corona electrode, and a part of the power will leave the discharge electrode in the form of radiation.

Conclusions. We solved the system of differential equations, modeling the processes of ionization in the discharge layer or in a hood of corona discharge. We obtained analytical dependences of ions and electrons densities in accordance with their diffusion due to the field intensity in ionization zone, fulfilled the analysis of corona hood structure and performed a diagram of the elementary processes in it.

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ЖҰМЫС ЖАСАУ АЙМАҒЫНДА АУАНЫ ОЗОНДАУ ҮРДІСІН МОДЕЛЬДЕУ

Аннотация. Агроөнеркәсіптік кешенінің жайларында ауаны озондауға арналған автоматтандырылған құрылғы ұсынылып отыр. Құрылғының құрамдас бөлшектеріне, атқаратын қызметтеріне және оның процестеріне сипаттама берілген. Жиілікті автоматты реттеу блогының техникалық сипаттамасында электронды және басқарушы элементтер келтірілген. Осы жұмыс ауада МП теріс озонирование тәжіндегі физикалық және химиялық процестерді зерттеудің теориясы мен әдіснамасын оқуға бірінші талпыныс болып табылады. жоғары энергия тиімділігі және озон өнімділігі озон Корона разрядты жаңа нұсқаулардың дамыту үшін алғышарттар жасауға мүмкіндік берді разряд осы түріне механизмі және озон electrosynthesis зерттеудің кинетика нәтижелері. өнеркәсіп, медицина және ауыл шаруашылығы түрлі секторларында озонды қолдану туралы мәліметтерді жүйелеу, айтарлықтай жалпы озон технологиясы қолдану аясын кеңейту.

Түйін сөздер: ауаны озондау, озон концентрациясы, жиілікті реттеу, ауаны озондауға арналған автоматтандырылған құрылғы.

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МОДЕЛИРОВАНИЕ ПРОЦЕССА ОЗОНИРОВАНИЯ ВОЗДУХА В РАБОЧЕМ ОБЪЕМЕ

Аннотация. Представлена автоматизированная установка для озонирования воздуха в помещениях агропромышленного комплекса. Дано описание исполняемых функций и процессов, комплектующих частей и компонентов установки. В техническом описании блока автоматического регулирования частоты приведены электронные и управляющие элементы. Разработка высокоэффективных озонных технологий и озонирующих устройств имеет большое значение и требует исследования теоретических положений и анализа экспериментальных данных, совокупность которых позволила бы развить научно-обоснованный методический аппарат проектирования данных систем с учетом требований, предъявляемых пищевой промышленностью. Настоящая работа является первой попыткой изучения теории и методики исследований физико-химических процессов озонирования в отрицательной короне с МП в атмосферном воздухе. Полученные результаты исследований механизма и кинетики электросинтеза озона в этом виде разряда позволили создать предпосылки для разработки новых принципов озонаторов на коронном разряде с более высокими энергетическими выходами озона и производительностью. Систематизация данных по применениям озона в различных отраслях промышленности, медицине и сельском хозяйстве, существенно расширяют область применения озонной технологии в целом.

Ключевые слова: озонирование воздуха, концентрация озона, регулировка частоты, автоматизированная установка для озонирования воздуха.

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ISSN 2518-170X (Online), ISSN 2224-5278 (Print)

http://geolog-technical.kz/index.php/kz/

Верстка *Д. Н. Калкабековой*

Подписано в печать 15.02.2017.
Формат 70x881/8. Бумага офсетная. Печать – ризограф.
15,25 п.л. Тираж 300. Заказ 1.

Национальная академия наук РК
050010, Алматы, ул. Шевченко 28, т. 272-13-19, 272-13-18