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WAYS TO IMPROVE THE EFFICIENCY IN PERFORMANCE OF CORONA DISCHARGE OZONATORS

Abstract. This article analyzes several ways to increase the corona discharge current in ozonators, which can further improve the ozone efficiency and reduce the specific energy consumption of the ozonating element at low air pressures in the discharge zone. Their capabilities, advantages and disadvantages when used in ozonating elements are described. The dependences of the voltages on the air pressure for different constant values of the discharge current measured at pressures starting from 100 mm Hg up to a pressure of 680 mm Hg at normal air temperature of 20°C are shown. The obtained data show that when the current values are constant and the pressure decreases, it turns out that the voltage decreases as much as the energy consumption increases. A table has been compiled that records the ozone efficiency and specific energy costs, as well as the corresponding values of voltages and currents for the three pressures, where it can be established that at low air pressures, it is possible to obtain fairly high values of specific energy consumption (166 g/kWh), which is the main advantage of the described method of obtaining ozone. In order to use the existing dependence of the discharge current value on the ambient air pressure, the effect of a natural pressure drop in the discharge zone due to the electric wind was tested when the ion-convection pump mode is observed. A method has been developed for air exhausting out of the working volume of the ozonizing element, which in turn involves the passage of ozonized air through the exhaust device, which ultimately significantly reduces the efficiency of obtaining ozone. This problem is solved with the help of an electric wind that occurs in the corona discharge zone; and a pressure drop around the corona element is observed.

Keywords: corona discharge, ozone, ozonator, the corona needle, productivity, energy consumption.

A method of producing ozone in electric discharges is the safest and most effective of all known, which is characterized by an optimal ratio of energy consumption to the concentration of ozone produced.

Corona discharge (one of the types of electrical discharge) occurs in a gas in a strongly inhomogeneous electric field between two electrodes – a high voltage and grounded separated by a gap (discharge gap) and a dielectric. Ozone is produced by the dissociation of oxygen molecules into the corona layer caused by electron impact.

The results of theoretical and experimental research of recent years have shown that a negative corona discharge with microelectrodes (microwires, the needle (the tip), sharp edges and a thin spiral with radii of curvature of not more than 25-50 microns) compared with other types of corona discharge provides a higher specific discharge current and a large current density on the corona electrode [1,2].

The ozone performance of any ozonized element primarily depends on the magnitude of the discharge current, and thus in order to reduce the specific energy consumption it is necessary to reduce the voltage values in the same discharge current. There are several ways to strengthen the corona discharge current, which leads to the increase of ozonized element productivity. Consider their possibilities, advantages and disadvantages when they are used in ozonized elements.

One of the ways to strengthen the corona discharge current, which is equivalent to increasing productivity of ozonized element, is to reduce the distance between electrodes of the discharge gap. In this case, at the same supply voltages it is possible to obtain higher values of the discharge current, if the breakdown between the electrodes does not occur.

Another way of strengthening the discharge current is to heat the corona electrode or to heat the air surrounding the discharge gap. In this case, with the increase of temperature the ionization rate in the discharge layer increases due to the increase of the length of free path of electrons, thus the current density in the outer area of the corona increases considerably. It was found that when air is heated up to 140°C and at the same voltage values the discharge current increases in five times, but the application of this method to strengthen the discharge current is caused by a number of technical difficulties: the need for an additional device to heat the air and then to blow it through ozonized element, and the thermal insulation of ozonized element from the environment is required as well. Furthermore, at such air temperature (140°C) one can only decompose ozone produced in ozonized element.

Another way to improve performance of ozonized element is to use pure oxygen instead of air. Indeed, in this case, the ozone output increases almost in two times. The reason hindering the use of this method is its high cost. Furthermore, under production conditions the use of oxygen does not meet the safety requirements.

One of the most effective ways to reduce specific energy consumption in obtaining ozone is the performance of ozonized element at lower air pressures. In this case, the only way to apply this method is to suck off the air from working volume of ozonized element, which provides passing the ozonized air through the aspirator and ultimately the effectiveness of obtaining ozone considerably reduces. This problem was solved by [4] using the electrical wind which occurred in the corona discharge zone, and it was found that the pressure around the discharge element decreased.

The results of the research showed that in the whole range of temperature and air pressure the characteristics of corona discharge are the functions of air density. The impact of temperature on the corona discharge is described by the same laws as the dependence of the air density on the temperature. Air pressure or its density has an influence on the amount of the discharge current through the initial field strength of corona discharge, which determines the firing voltage at a given interval [5].

Based on the numerous measurements of the initial voltage of corona discharge Peak managed to give the empirical formula for the initial field strength of corona occurring on the surface of the corona wire with a radius r_0 [6]. The comparison of the calculated and experimental data shows [7,8] that in general the best convergence (for coaxial cylinders) can be obtained for the following Peak formula:

$$E_0 = 30{,}3\delta(1+\frac{0{,}298}{\sqrt{r_0\delta}} \qquad (1)$$

where δ - relative air density, which is defined by the formula:

$$\delta = \frac{0{,}386p}{273+T} \qquad (2)$$

where p - barometric pressure, $mmHg, T$ –air temperature, °C; $\delta = 1$ under atmospheric conditions adopted for the normal (p = 760 mm Hg, T = 20°C).

The impact of E_0 on the value of corona discharge current can be determined by the initial voltage U_0 (1) onvolt-ampere characteristic of corona discharge, Townsend formula is given as an example [8].

$$I = \frac{8\pi\varepsilon_0 k(U-U_0)U}{R^2 \ln\frac{R}{r_0}} \qquad (3)$$

where ε_0 - dielectric constant, and κ - mobility of ions, U - voltage between electrodes, U_0 - initial voltage of corona discharge.

It is advisable to check the conformity of the experimental values of corona discharge ignition voltage with the calculated ones by Peak formula (1). Table 1 shows the experimental results of measurements and the calculated values of initial voltage U_0, U_C and field intensities of corona E_0, E_C depending on pressure and air temperature. All measurements and calculations are referred to negative corona discharge.

The values δ, given in the tablewere calculated by the formula (2). Using the formula (1) the tension on the surface of the corona wire can be calculated using the experimental values U_0. While the values U_0

are measured by the sufficient accuracy (0.1%), a large error may be introduced due to the unevenness of the diameter along the length of the corona wire in the determination of E_0 by the formula (1).

The table of data analysis shows that in most cases the values E_C are greater than values E_0. The difference between E_0 and E_C does not depend on ρ and T and makes 3% on average, whereas values E_0 may be changed with respect to E_C with increasing temperature sometimes up to 7%.

It was found out [9] that primarily the decrease of air density tended to reduce the value of the initial voltage of corona discharge, thus, the volt-ampere characteristics significantly increased.

Now consider the output parameters of ozonized element at low air pressures, which include the performance of ozone (g/h) and specific energy consumption (g/kWatt·h). To do this, we use the characteristics of ozonized element, obtained in work [9, p. 169, figure 57], and approximating it we find a formula for the dependence of the ozone on corona discharge current:

Table 1 – Initial voltage and tension of corona field (atm.air R = 0,5 cm, r_0 = 0,0025 cm)

p, mmHg	T, °C	Δ	U_0, V	E_0, кV/cm	E_C, кV/cm formula (3)	U_C, V formula (1)
100	24,5	0,133	1000	75,5	72,5	955
80	24,5	0,266	1400	105	107	1420
300	24,5	0,399	1750	132	132,3	1755
400	24,5	0,532	2050	155	156	2065
500	24,5	0,665	2300	173	176	2330
680	24,5	0,903	2700	204	209	2770
680	40,0	0,852	2520	190	203	2690
680	60,0	0,801	2460	185	196	2600
680	80,0	0,755	2400	181	189	2510
680	100	0,715	2350	177	183	2423
680	120	0,678	2260	170	178	2360
680	140	0,648	2200	166	173	2290

$$P_p = KI \tag{4}$$

Where P_P – ozone productivity (g/h), K - coefficient of proportionality (g/h·mA), I - discharge current (mA). Using the magnitude of the inclination angle characteristics we can calculate the value of the proportionality coefficient K = 0.2 g/h·mA.

Specific energy consumption (P_S) is determined by the ratio of ozone productivity (P_P) to the energy consumption W = U·I kW per hour, that is:

$$P_s = \frac{P_p}{W} = \frac{KI}{UI}\text{, g/kWatt/h} \tag{5}$$

where U - voltage between the electrodes, kV, I - discharge current, A.

In fact, at a certain current P_S depends only on the value U, the smaller its value, the higher P_S. The comparison of the experimental values P_{PE} with the calculated P_{PC} by the formula (4) is of great interest. To illustrate this comparison we make a table which also includes the experimental values P_{SE}.

Table 2 – Ozone productivity and energy output of ozonated element

U, kV	5	5,6	6,1	6,4	6,6
I, mA	0,5	1,0	1,5	2,0	2,5
P_{PE}, g/h	0,09	0,25	0,36	0,45	0,5
P_{PC}, g/h	0,13	0,24	0,33	0,44	0,53
P_{SE}, g/kWatt/h	45	40	35	32	29

As can be seen from the data in table 2, the maximum difference between $P_{\text{ПЭ}}$ and $P_{\text{ПА}}$ does not exceed 8%, and therefore the determination of $P_{\text{П}}$for the other values of the discharge current according to the formula (4) leads to a small measurement error. The calculation formula (5) can be used to determine $P_{\text{У}}$.

Figure 1 shows the dependence of voltage (U) on the air pressure (p) for various values of the constant values of current discharge (I), measured at pressures ranging from 100 mm Hg. up to pressure of 680 mm Hg. under the air temperature 20°C as normal. From these data we can conclude that when the value I is constant and p is reduced it turns out that the less the value U is, the more P_S is.

In accordance with the law of states of ideal gas, the decrease of air pressure also reduces the concentration of oxygen molecules in the air that can lead to reduction of ozone formation in the discharge gap. Meanwhile, the decrease in p also leads to the opposite effect: strengthening the ionization processes due to the lengthening of the mean free path of electrons, and therefore, to the increase of their energy. Thus, the reduction of p cannot significantly influence on the degree of ozone output as when p is reduced the permanence of discharge current values is provided by the required density of charge stream which mainly consists of oxygen ions and ozone.

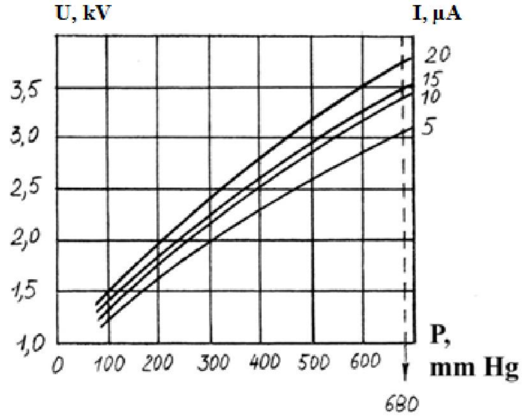

Figure 1 – Dependence of voltage on air pressure

Table 3 shows the productivity of the ozone (P_{PS}) and specific energy consumption (P_S), as well as the corresponding values of U and I for the three air pressure.

Table 3 – Output parameters of ozonated element at low air pressures

P, mm Hg.	100				400				680			
I, μA	5	10	15	20	5	10	15	20	5	10	15	20
U, kV	1,2	1,3	1,4	1,5	2,3	2,5	2,6	2,8	3,1	3,4	3,5	3,8
P_{PC}, g/ h	10^{-3}	$2\cdot10^{-3}$	$3\cdot10^{-3}$	$4\cdot10^{-3}$	10^{-3}	$2\cdot10^{-3}$	$3\cdot10^{-3}$	$4\cdot10^{-3}$	10^{-3}	$2\cdot10^{-3}$	$3\cdot10^{-3}$	$4\cdot10^{-3}$
P_S, g/kW/h	166	153	142	133	87	80	77	71	64	58	57	52

The main discharge processes under the corona needle and corona wires are not different fundamentally and they vary according to the electric field configuration and discharge power. In this regard, in order to study the impact of air pressure on characteristics of corona discharge there has been used the coaxial electrode system which is characterized by experimental simplicity and convenience, and it is also ozonized element for obtaining ozone in corona discharge.

As can be seen from the data in Table 3, at low air pressure it is possible to get quite high values of specific energy consumption (166 g/kW·h), which is the main advantage of this method of producing ozone.

In order to use the existing dependence of discharge current value on the air pressure, there has been tested the effect of natural pressure reduction in the discharge area due to the electric wind when there is an ion-convection pump mode.

A device was developed for producing ozone in a corona discharge zone, comprising a corona electrode in the form of needles and the outer electrode as a grid located in the tube with a plug made of ozone resistant insulating material (Teflon, Vinyl and etc.) [10].

The most advantageous modification is ozonator containing successive ozonized elements made in the form of "the corona needle - flat metal mesh", which are placed in the half-closed chamber and are arranged symmetrically in the direction of the electric wind, which occurs in the direction of the open side of the camera, the ozonator contains ozonized elements located near the closed part of the chamber and additional ozonator discharge electrodes located near the open end of the chamber for the narrow part circle section nozzle.

As it was noted, the principle of convection ion pump based on the known parameters of the electric corona wind that generally reduces the pressure in the discharge interval was used in the proposed design of the ozonator [11]. It was found that the decrease in pressure in the discharge zone allows you to raise the efficiency of the ozonator. Furthermore, it is expected that the effect of reducing the pressure in the interelectrode space to be more noticeable if a discharge system is placed in a half-closed chamber in such a manner that caused an electric wind is directed towards the open portion of the chamber. In the case of series, connection of several elements in the ozonized discharge chamber disposed symmetrically, the effect of reducing the pressure in the chamber to be more significant than a single corona needle. The total sum of the determined pressure differential $\Delta p = \Delta p_1+\Delta p_2+$ ... etc, and so the magnitudesof discharge currents of ozonated elements at the same potential differences tend to the increase.

A new design that allows to divide the processes of formation of ozone and the creation of an electric wind, which leads to the provision of a low specific energy consumption with a simple design [12].

Figure 2 represents a functional diagram of ozonator which operates in a semi-closed mode and consists of separate elements arranged ozonated and discharge electrodes to generate an electric wind. Ozonated elements 4 units in the form of electrode system as "needle-net" contain the discharge electrodes 1 and 2 to the external electrode grid disposed in a sealed portion of the tube 3 made of ozone resistant insulating material (Teflon, Vinyl and etc.). Corona electrode K is supplied from the power supply unit (PSU) of negative polarity high voltage, and the grid electrode 2 is grounded. The additionallycorona electrodes 4 attached to the grid electrode 2 and located near the open part of the edge portion of the circle narrow nozzle chamber section 5 (section AA) is used to create electric wind in ozonator chamber. The second electrode is a grid 6, which is attached to the open part of the tube and is connected to the positive pole of the power source.

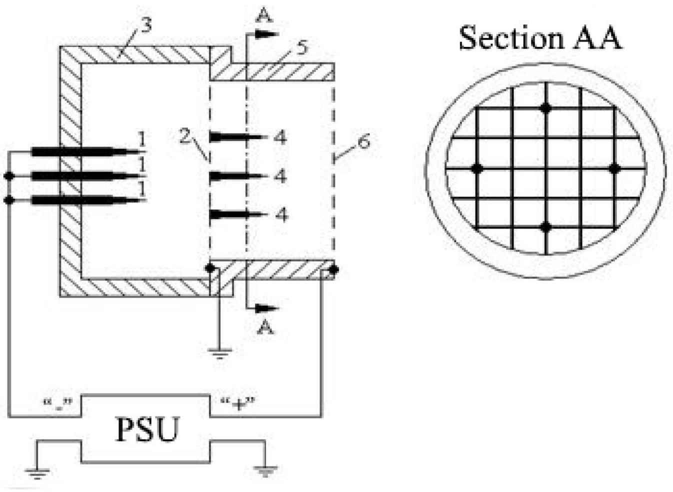

Figure 2 – Functional diagram of the ozonator

After the voltage (-U) of sufficient magnitude to the discharge electrodes, there is corona discharge between them and a grid electrode 2, and formed with a negative space charge, consisting essentially of oxygen ions and ozone tends to grid electrode 2 at a zero potential, wherein the partially neutralized, forming a molecule of oxygen and ozone, and most of the ions are accelerated towards the electrode 6 with positive potential.

Within the certain time (less than 5 seconds) there is set stable electric wind directed into the open part of the discharge chamber and the ozonator starts operate in the ion pump convection mode. At the same time, there is a gradual decrease in the air pressure within the discharge chamber and, as might be expected, it increases the force of the discharge current. This situation cannot last long as at some point begins the process of suction air through the outer wall region of the discharge chamber 5. To prevent wall surface in the air suction chamber, discharge electrodes are additionally installed on the edge of the circle fitting section narrowest part five (section AA). After some time, a stable set of low air pressure conditions inside the discharge chamber, which means that the prevalence of process air suction of external air into the process in the chamber.

Ozonated elements, 4 units have the following parameters: the radius of curvature of the needles r_o= 0.2 mm, the diameter of the insulating tube 16 mm, the distance from the tips of the needles to the grid equal to r_1= 6 mm, and supply voltage U of the discharge chamber was changed in the range of 4 to 14 kV. When you turn on the power supply voltage of 10 kV initially, the average current of the discharge chamber was equal to 30 mA. Afterwards, when establishing steady mode of electric wind in the open part of the discharge chamber, the current increases gradually reaching 38 mA. To determine the specific energy consumption of the device (g/kV/h) in one or the other case, the use of the calibration curve removed ozonometer type LEK designed by St. Petersburg technical university for ozonated element in the corona discharge. On average, the specific productivity of ozonated element makes 0.8 grams of ozone per hour with the power of 4 mA discharge current. On this basis, we calculate the specific power outputs of the device in different operational modes. In this specific energy output of the device at atmospheric air pressure of 680 mm Hg (Almaty) and at the initial time is 20 g/kV/h, while at steady mode of electric wind it was 23,5g/ kV/h. In the second mode, in order to maintain the initial discharge current 8 mA, it is necessary to reduce the power supply voltage to 8, 5kV, which ultimately leads to a reduction in specific energy consumption for the production of ozone in the corona discharge.

The comparison of value of the power supply reduction at a constant discharge current of known voltage dependence of corona discharge off air pressure [13] allows approximately determine the air pressure in the discharge area, for example, in our case, air pressure reduction relatively to atmospheric (680 mm Hg) was about 100 mm Hg.

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ТӘЖДІ РАЗРЯД НЕГІЗІНДЕГІ ОЗОНАТОРЛАР ЖҰМЫСЫНЫҢ ТИІМДІЛІГІН АРТТЫРУ ЖОЛДАРЫ

Аннотация. Берілген мақалада озонаторлардағы тәждік разряд тоғын күшейтудің бірнеше жолдары қарастырылған, олар озон өнімділігін одан әрі арттыруға және разряд маңайындағы ауа қысымы төмен болған кезде озондаушы элементтің нақты энергия шығынын азайтуға мүмкіндік береді. Озондаушы элементтерде қолданылған кездегі олардың мүмкіндіктері, артықшылықтары мен кемшіліктері сипатталады.

Ауа температурасын 20 °С қалыпты деп алып, 100 мм.с.б. бастап 680 мм.с.б. дейінгі аралықтағы қысыммен өлшенген разрядтық тоқтың *(I)* әртүрлі тұрақты мәндеріі үшін кернеудің *(U)* ауа қысымына *(P)* тәуелділігі келтірілген. Алынған мәліметтер бойынша тоқтың мәндері тұрақты және қысым төмендеген жағдайда кернеудің қаншалықты төмендегенімен энергия шығыны соншалықты өсетіні көрінеді.

Тәждеуші инедегі және тәждеуші сымдарда өтетін негізгі разрядтық процестер түбегейлі ерекшеленбейді және олар электр өрісінің конфигурациясында және разрядтан болатын қуатпен ерекшеленеді. Осыған байланысты ауа қысымының тәждік разряд сипаттамаларына әсерін зерттеу үшін экспериментадды қарапайымдылыққа ие болатын және ыңғайлы болып келетін электродтардың коаксиалды жүйесі қолданылды, сонымен қатар ол тәжді разрядта озон алуға арналған озондаушы элемент болып табылады.

Озонның өнімділігі мен энергияның меншікті шығындарын, сондай-ақ қысымның үш түрлі мәндері үшін кернеулер мен тоқтардың тиісті мәндерін анықтайтын кесте жасалды, мұнда ауа қысымы төмен болған кезде энергияның меншікті шығындарының айтарлықтай жоғары шамасын (166 г/кВт·сағ.) алуға болатындығы анықталды, мұның өзі сипатталған озон алу әдісінің басты артықшылығы болып табылады. Ауа тығыздығының төмендеуі, ең алдымен, тәжді разрядтың бастапқы кернеуінің төмендеуіне әкелетіні анықталды және бұл жағдайда вольтамперлік сипаттамалардың тұрақтылығы айтарлықтай артады.

Разряд тогының қоршаған ортаның қысымына тәуелділігін қолдану мақсатында разряд маңайындағы қысымның электрлік жел әсерінен табиғи түрде төмендеу құбылысы зерттелді, осы кезеңде иондық-конвекциялық сорғы режимі байқалды.

Ауаның температурасы мен қысымының барлық диапазонында тәждік разрядтың сипаттамалары тек ауа қысымының функциялары болып табылатынын көрсететін зерттеулер нәтижелері келтірілген. Ауа температурасының тәждік разрядқа әсері ауа тығыздығының оның температурасына тәуелділігімен бірдей сипатталады.

Тәждік разрядтың тоқ күшіне түсетін ауаның қысымы немесе оның тығыздығы тәждік разряд өрісінің бастапқы кернеулігі арқылы әсер етеді, өз кезегінде ол берілген аралықта разряд пайда болуының кернеуін анықтайды. U_0 тәжірибелік мәндерін тиісті формулаларға қойып, тәждеуші сымның бетіндегі кернеулік есептелген. U_0 мәндерін жоғары дәлдікпен (0,1%) өлшеген кезде, кернеулікті анықтау барысында тәждеуші сымның ұзындығы бойынша біркелкі еместігіне үлкен қателік енуі мүмкін болатындығы байқалды. U0 E0 формуласы бойынша анықтаған кезде (1), ұзындық бойынша корона сымының біркелкі болмауына байланысты үлкен қате пайда болуы мүмкін. Төмендетілген ауа қысымындағы озондаушы элементтің шығу параметрлері, яғни озонның өнімділігі (г / сағ.) және энергияның меншіктік шығыны (г / кВт.сағ) анықталды.

Авторлар озондаушы элементінің жұмыс көлемінен ауаны сорып алу әдісін жасады, бұл өз кезегінде озондалған ауаның сору қондырғысы арқылы өтетінін, нәтижесінде озон алудың тиімділігінің айтарлықтай төмендейтінін болжайды. Бұл мәселе тәжді разряд маңайында пайда болатын электрлік жел көмегімен шешіледі және тәждеуші элементтің айналасындағы қысымның төмендеуі анықталды.

Түйін сөздер: тәжді разряд, озон, озонатор, тәждеуші ине, өнімділік, энергия шығыны.

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ПУТИ ПОВЫШЕНИЯ ЭФФЕКТИВНОСТИ РАБОТЫ ОЗОНАТОРОВ НА КОРОННОМ РАЗРЯДЕ

Аннотация. Рассмотрены несколько путей для усиления тока коронного разряда в озонаторах, которые могут позволить дополнительно повысить производительность по озону и снизить удельные энергозатраты озонирующего элемента при пониженных давлениях воздуха в зоне разряда. Описаны их возможности, достоинства и недостатки при применении их в озонирующих элементах.

Построены зависимости напряжений от давления воздуха для различных постоянных значений тока разряда, измеренных при давлениях, начиная от 100 мм рт. ст. вплоть до давления 680 мм рт. ст., считая температуру воздуха нормальной 20 °С. Полученные данные показывают, что при постоянстве значений тока и в случае снижения давления оказывается, что на сколько снижается величина напряжения, на столько повышается энергетические затраты.

Основные разрядные процессы при коронирующей игле и при коронирующей проволоке принципиально не отличаются и разнятся они по конфигурации электрического поля и по мощности разряда. В связи с этим для исследования влияния давления воздуха на характеристики коронного разряда была использована коаксиальная система электродов которая обладает экспериментальной простотой и удобством и также является озонирующим элементом для получения озона в коронном разряде.

Составлена таблица, фиксирующая производительность по озону и удельные энергетические затраты, а также соответствующие значения напряжений и токов для трех давлений, где можно установить, что при пониженных давлениях воздуха можно получить довольно высокие значения удельных энергозатрат (166 г/кВт·ч), что является основным преимуществом описанного способа получения озона. Установлено, что уменьшение плотности воздуха, в первую очередь, ведет к снижению значения начального напряжения коронного разряда, причем крутизна вольтамперных характеристик при этом заметно увеличивается.

С целью использования существующей зависимости значения тока разряда от давления окружающего воздуха был опробован эффект естественного понижения давления в зоне разряда из-за электрического ветра, когда наблюдается режим ионно-конвекционного насоса.

Приведены результаты исследования, показывающие, что во всем диапазоне температур и давлений воздуха характеристики коронного разряда являются функциями только плотности воздуха. Влияние температуры воздуха на коронный разряд описывается той же закономерностью, что и зависимость плотности воздуха от его температуры. Давление воздуха или плотность его на величину силы тока разряда влияет через начальную напряженность поля коронного разряда, которая в свою очередь, определяет напряжение возникновения разряда в данном промежутке.

Используя экспериментальные значения U_0, по формуле (1) вычислена напряженность на поверхности коронирующего провода. Обнаружено, что тогда как значения U_0 измеряются достаточно с высокой точностью (0,1%), при определении E_0 по формуле (1) может вноситься большая погрешность из-за неравномерности диаметра коронирующего провода по длине. Определены выходные параметры озонирующего элемента при пониженных давлениях воздуха, к которым относятся производительность по озону (г/ч) и удельные энергетические затраты (г/кВт.ч).

Авторами разработан способ отсасывания воздуха из рабочего объема озонирующего элемента, что в свою очередь предполагает прохождение озонированного воздуха через отсасывающее устройство, при котором в конечном итоге, в значительной степени снижается эффективность получения озона.

Данная задача решена с помощью электрического ветра, возникающего в зоне коронного разряда, и установлено понижение давления вокруг коронирующего элемента.

Ключевые слова: коронный разряд, озон, озонатор, коронирующая игла, производительность, энергозатраты.

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