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IMPROVING THE EFFICIENCY OF ELECTROSTATIC PRECIPITATORS

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This paper provides information on the achievements in development of gas cleaning. A critical analysis of functioning principle of electrostatic precipitators, which are currently being developed and operated, is conducted. The possibility of increasing the effectiveness of gas cleaning using unipolar voltage pulses has been analyzed. It has been found that a streamer mechanism of discharge or streamer shape of corona discharge is the case, when voltage pulses with overvoltage are used and electrostatic precipitators run. The most rational circuit for unipolar voltage pulses generation using low-voltage generators of periodic voltage pulses is identified. To separate space charges formed in the streamers' channel, it is proposed to use pulsating voltage with a direct component and a potential plane with corona needles–grounded plane electrode system. The analysis of transient process within feed circuit of discharge technological gaps has shown that cut-off pulse repetition frequency, in which stability of discharge current is ensured, depends on the parameters of feed circuit elements and the discharge gap capacitance. It was found that the use of corona discharge streamer form allows increasing the speed of the gas to be purified up to 8 m/s, and reducing the aerosol particles deposition zone to 1 m. The gas velocity is 1 m/s with a deposition zone of more than 27 m in an existing gas filling device (GFD) type electrostatic precipitator. When comparing these indicators, the energy intensity of the process decreases by more than 100 times, and the specific power of the gas flow purification process is 33 (W·s)/m^3.

KEY WORDS: *gas cleaning, corona discharge, electrostatic precipitators, electric discharge, stabilization, streamer form of corona discharge*

1. INTRODUCTION

The large volumes of harmful emissions into the atmosphere cause a number of adverse global and regional events. In most countries, payments are made for emissions of harmful substances into the environment. However, not all payments motivate enterprises to introduce cleaning measures. For example, in the Republic of Uzbekistan, the fee for releasing the emission into the atmosphere of 1 ton of cotton dust is $0.20. It is more profitable for enterprises to make those payments rather than to introduce and operate treatment structures and installations. Similar enterprises in the EU member-countries are closed upon compensation of the harm inflicted by nature.

Various methods and devices are used to treat process gases, the most preferred of which are electrostatic precipitators with their distinctive features such as high clean ability, high treated gas capacity, ability to catch aerosol particles of size less than 0.1 μm with any physical and mechanical properties, and lack of aerodynamic drag.

Development of electrical gas cleaning techniques falls between the 50s–80s of the last century (Levitov, 1980; Aliev, 1981, 1986). Apparatuses ensuring high degree of cleaning have been created; the application domain of electrostatic precipitators has extended significantly. Production of unified dimension-type electrostatic precipitators has been set, a number of which include high-production apparatuses that ensure cleaning of flue gases emitted from the boilers of large 300, 500, and 800 MW power units, large cement production furnaces, and other processing apparatuses.

From the 80s of the 20th century, main works on gas cleaning are mainly associated with increasing the effectiveness and reliability of already developed electrostatic precipitators. Owing to application of tyristor control, silicon rectifiers, and other semiconductors, reliability of generating units has improved greatly. The developed principles of voltage control enabled one to maintain an increased load on electrostatic precipitators' electrodes, which ensure a high degree of cleaning (Aliev, 1981).

However, the use of electrostatic precipitators is constrained by a number of factors.

It is important to note here, first of all, the significant sizes and mass of electrostatic precipitators under high power consumption. The sizes of GFD-series electrostatic precipitators range from $18.6 \times 12 \times 15.4$ m to $24.8 \times 21.8 \times 27$ m, the deposition zone of the aerosol particles being $A_1 = 15.4–27$ m. Power sources of up to 200 kVA capacity are used to feed the electrostatic precipitators. Flow rate of the cleaned gas is $V_1 = 1–1.5$ m/s.

If the settling zone A_1 is reduced to the magnitude A_2 and the gas flow rate V_1 is increased up to the value V_2, then power consumption of electrostatic precipitators under same cleaned gas treatment capacity will reduce $[(V_1 / V_2)(A_1 / A_2)]$ times. The sizes of electrostatic precipitators will reduce *pro rata* to the capacity.

The gas cleaning effectiveness can be increased by using pulsating voltage of low duty cycle, using the regularity of an increase in electric gas strength when voltage dwell time reduces (Kostenko, 1973; Korolev and Mesyats, 1991; Putri et al., 2010).

Powerful high-voltage commutating semiconductors have been created recently, which enables resolution of technical problems of creating reliable pulse power supply units (Skolskiy, 1980; Kolek and Holub, 2019). However, the information given in the literature does not provide any practical recommendations as to design of industrial apparatuses, what is more — lack of pilot research recurrence and discord of the results cast doubt on expediency of switched power supply. This happens due to the lack of a convincing physical model explaining the very impact mechanism of the switched power supply on dust collection effectiveness. It should be noted that these supply sources were used to increase the effectiveness of the electrostatic precipitators operated. Moreover, they provide for commutation of voltage pulses under high frequency of 12–24 kHz.

Several original devices have been proposed in the field of gas purification over the past 5–6 years. These include electret filtering materials with a low pressure drop and high filtration efficiency (He et al., 2020). The disadvantage of this device is a low electric field strength and inability to regulate the process.

Electrostatic filters have been developed for cleaning gaseous media from coal dust for enterprises focused on fuel and energy production activities (Tatevosyan et al., 2018). In these filters, the use of electric pulsed cleaning devices is proposed for shaking off the deposited layer of coal dust from the precipitation electrode. However, such periodic cleaning devices lead to secondary entrainment of already deposited dust.

In many applications, electrostatic precipitators are particularly attractive for the thermal treatment of radioactive materials (Meivita et al., 2018). In these studies, to increase voltages above breakdown voltage, the use of new power sources combining direct voltage with pulsating voltage is proposed. In this case, the high-voltage power supply circuit becomes much more complicated, where it is necessary to use two high-voltage sources: direct and pulsating.

The proposed electrostatic filter is an ozone generator consisting of a plate corona discharge and a high-voltage direct current generator (Lemont et al., 2018). The experimental results showed that the more ozone generators used as electrostatic filters, the faster the concentration of particles decreases. However, studies on the processes of ozone electrosynthesis showed that they have very low energy indices, and ozone output efficiency does not exceed 2%.

In studies conducted by Malcher (2017), an attempt was made to functionally treat the surface of a discharge electrode to reduce the level of ozone generation from a corona discharge. Industrial ozone generators were based on a barrier discharge powered by an alternating current source, while the voltage on the ozone generator significantly exceeds the discharged voltage without a barrier. Our studies have established that the concentration of ozone at the outlet of the electrostatic precipitators does not exceed the maximum permissible concentration (MPC).

Filtration of dust treated with an electric field, with and without corona discharge, was investigated on a laboratory scale (Hyun et al., 2017). An increase in the pressure drop across the dust crust was detected when an electric field was applied without a corona discharge. If a corona discharge exists, the pressure drop decreases. The influence of dust pre-charging on the pressure drop after regeneration of the filter at low filter loads was indicated.

In the studies carried out by Shimizu et al. (2016) and Feng et al. (2016), a new electrostatic air filter system (EEAF) was proposed, which could increase the filtering efficiency of the fibrous filter for small particles without increasing a pressure drop.

Indoor air quality was improved by monitoring particulate matter (PM), consisting of components such as house dust and bacteria, using atmospheric pressure plasma (Malcher, 2017).

Fedorov et al. (2013) presented materials for studying detachment with impact for dust deposited in the field of an electric corona discharge on filter electrode plates. It was found that a significant factor determining the level of acceleration required to separate dust from the electrodes is the weight of dust accumulated on the electrodes before shaking off.

However, in the aforementioned works, the goal was not to increase the efficiency of the electric gas treatment process, reduce the weight, dimensions, and power consumption, and increase their productivity in the cleaned air. The listed parameters are the determining technological parameters, but in many studies they are simply not even mentioned. An important drawback in these works is also the lack of developments in the management of the processes for operation of electrostatic precipitators and their automation.

2. STUDY OBJECTIVES

In connection with the foregoing, a main objective of this study was the justification and development of a new gas purification method.

To achieve this goal, the following tasks were solved:

- Analysis of the problems of constant-voltage corona discharge.
- Development and confirmation of recommendations for stabilization of discharge processes in the corona discharge.

3. MATERIALS AND METHODS

A theoretical analysis of the processes in the discharge gap was carried out using the existing theory of electric discharges in gases. Processes in pulsating electric fields were investigated in Kostenko (1973) and Korolev and Mesyats (1991). In these works, the main conclusions are based on process observations, experimental studies, and their analysis. Based on the analysis of these data, it is possible to establish a discharge mechanism in a sharply inhomogeneous electric field at pulsating voltage.

A preliminary study of the stabilization processes and determination of the optimal characteristics of discharges were performed by the mathematical modeling method. A linear piecewise approximation program with a time integration step was used for the mathematical modeling.

After obtaining the results from the mathematical modeling, field experiments were carried out, which allowed refining the calculated results and confirming their validity.

4. RESULTS AND DISCUSSION

4.1 Theoretical Process Analysis

First of all, it was necessary to establish a mechanism for the development of a discharge in air under pulsating overvoltage.

The current pulses of a DC corona discharge are randomly distributed in time and represent a function of a discrete, random process, the implementation of which is random in amplitude and frequency (Sokolskiy, 1980). It follows from the foregoing that stabilization of discharge processes in electric fields of a corona discharge will significantly increase the efficiency of electrostatic precipitators.

Various concurrent elementary processes—emergence, motion, and elimination of charged particles—occur in corona discharge, like in all types of self-maintained discharges. Law-based quantitative derivation of discharge properties works only in some cases for now, and besides provided that significant assumptions are introduced. This takes place owing to mathematical difficulties that arise once various regularities are combined. Such types of discharges are commonly referred to as self-maintained. The above properties of direct voltage corona discharge lead to instability of discharge currents in frequency and amplitude, discharge blocking, reverse corona, transition into spark or arc shapes. It is obvious that gas cleaning effectiveness can be increased if ensuring stability of discharge processes.

It is easiest to look into discharge phenomena in cases when only motion rather than emergence of electrons and ions has to be taken into account. Such discharges are called non-self-maintained and, unlike the self-maintained ones, are more stable. This yields the *hypothesis* on the possibility to stabilize discharge processes by combining self-maintained and non-self-maintained discharges in one technological gap. From the standpoint of technological application of the said hypothesis, except for the main technological gap with strength less than the self-maintained discharge ignition threshold, an auxiliary discharge gap ensuring delivery of the required quantity of space charges to the main gap is needed. To implement such a circuit, two isolated high-voltage sources are required. Such circuit is technically feasible, but will virtually lead to significant sophistication of the electrostatic precipitator structure, increase in its size and the power consumed under cost increase.

Combining self-maintained and non-self-maintained discharges in one technological gap with a single power source is of scientific and practical interest. This can be achieved, for instance, by using unipolar pulsating voltage of low duty cycle with a direct component lower than the self-maintained discharge ignition threshold. In this case, the pulsating voltage should be characterized by the following parameters (Fig. 1):

- pulsating voltage amplitude – U_a, V;
- direct voltage pulse component – U_d, V;
- effective voltage – U_e, V;
- pulse duration – τ_{pulse}, s;
- pulse repetition cycle – T_{pulse}, s;
- pulse duty cycle – $K = T_{pulse} / \tau_{pulse}$;
- pulse frequency – n, s^{-1};
- breakdown voltage DC corona discharge – U_b, V.

When using direct voltage to feed discharge gaps, power sources are chosen according to the voltage magnitude and the current. All above-specified parameters will influence the processes taking place within an electric field when fed by pulsating voltage.

It appears problematic to study the regularities of the pulsating voltage parameters' relationship, including internal resistance of the power source and dynamics of the processes in overvoltage discharge.

Given applied nature of our scientific work, it would be wise to choose a required type of voltage pulse and a real generating circuit. In this case, the pulse parameters and shape, duty cycle, duration and edge will be characterized by the generating circuit, which should meet the following requirements:

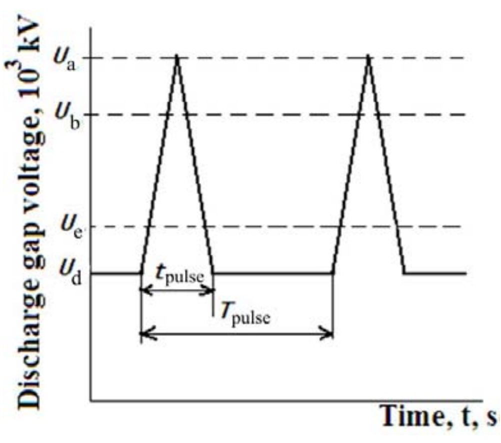

FIG. 1: Parameters of high-voltage unipolar pulses to implement the method of combining self-maintained and non-self-maintained discharges in one discharge gap

- ensure stability of frequency, shape, and amplitude of voltage pulses;
- have minimum sizes, simplicity, and reliability given minimum cost;
- resolve the possibility of transition of partial air breakdown into spark and arc discharges;
- create voltage pulse shapes on low-voltage side of step-up transformer, in the generating circuit;
- meet the requirements of electrical and fire safety and industrial sanitation;
- be radio quiet.

Some time passes, called the delay time t_{delay} with a pulsed breakdown of gases between the moment of application of voltage to the gap and the beginning of the breakdown, which is recorded by a sharp drop in voltage. The lag time is most often measured from the moment when the voltage reaches breakdown, until it drops to the level of $0.9U_a$, where U_a is the pulse amplitude. The onset of gas breakdown is identified with a sharp drop in voltage. Then the processes of increasing conductivity in the delay stage are called prebreakdown phenomena. This separation is largely arbitrary, since the current level that determines the voltage drop depends on the resistance of the external electrical circuit.

Recession can occur in various phases of the increase in the gap conductivity, i.e., depending on the resistance of the circuit, it can be due to various physical processes that cause an increase in the concentration of charged particles. However, a universality of the situation lies in the fact that before the start of ionization phenomena in the gap it is necessary to have at least one initiating electron. Therefore, it is customary to break the time t_{delay} into two components: the statistical delay time t_{st} during which the initiating electron appears in the gap, and the formation time t_f, during which the breakdown originates due to the development of the primary electron avalanche and subsequent stages of ionization increase.

Depending on the growth conditions, the number of carriers in a single electron avalanche can develop according to the Townsend or streamer mechanism.

A distinctive feature of the Townsend breakdown mechanism is that a space charge of a single electron avalanche practically does not distort the electric field in the gap, i.e., the number of electrons in the avalanche is less than a certain critical value N_{cr}.

A criterion for streamer breakdown is a condition that the number of electrons in the avalanche is greater than or equal to the critical value N_{cr}.

When the number of electrons reaches N_{cr}, an avalanche is characterized by a set of features in which a streamer discharge can occur. An avalanche emits enough photons to photoionize the gas in the amplified field region.

The excess magnitude of the voltage pulse amplitude (U_a) over the breakdown threshold of the constant voltage ($U_{br.const}$) is characterized by an overvoltage coefficient:

$$K_{th} = U_a / U_{br.const} .$$

The overvoltage coefficient value is inversely proportional to the front and the duration of the pulse. It plays a decisive role in the transition from the Townsend mechanism to the streamer mechanism. Figure 2 (Korolev and Mesyats, 1991; Putri et al., 2010) shows a curve dividing the set of values of the product of gas pressure by the gap length and the coefficient K_{th} into two regions. If the discharge conditions correspond to the region lying above the curve, then the streamer breakdown mechanism takes place, and if lower, the Townsend one. In the border region, one or another type of breakdown can be observed.

In the corona discharge technique, gaps from 0.05 to 0.15 m (Levitov, 1980; Aliev, 1981, 1986) are used at pressures close to normal, which corresponds to $p_d = 3800–8000$ Torr·cm. Therefore, even at $K_{th} > 4\%$, the streamer breakdown mechanism is manifested.

According to the studies based on the characteristics of pulsating voltage, the overvoltage coefficient, depending on the magnitude of the load, was 1.4–1.6. The amplitude of the voltage rise, in the limit of the pulse frequencies used in the research (50–500 pulse^{-1}), is 20–200 kV/μs. In this study, the distance between the electrodes of 0.05 and 0.1 m was used. Based on the analysis, it is inferred that the discharges have a streamer mechanism, or streamer form of a corona discharge (Kostenko, 1973).

4.2 Mathematical Modeling of Processes Providing Stabilization of Discharge Processes under the Influence of Pulsating Voltage

The process occurring in the discharge gap in the pause between pulses under the action of the voltage pulse's constant component is of interest. The voltage pulse's constant component is below the ignition threshold of the self-discharge, therefore, there are no discharge processes in the pause between pulses in the discharge gap.

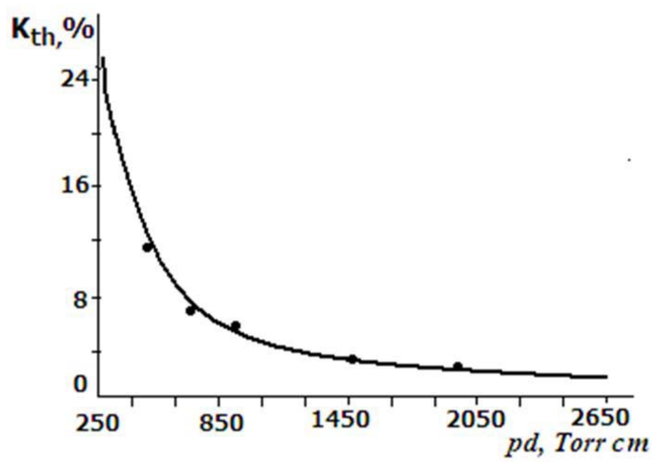

FIG. 2: Curve dividing the discharge development regions by the Townsend and streamer mechanisms

The issue of discharge process stabilization in terms of currents (in our case, currents occur under the influence of a voltage pulse and currents in the pause between pulses) can be solved by choosing a pulse repetition rate such that during the pause between pulses all the processes of motion and recombination of charged particles will be brought to the extent to which they practically do not affect the conductivity of the discharge gap, i.e., the current through the discharge gap at the end of the pause should be zero. The presence of space charges in the discharge gap distorts the picture of the main electric field, which characterizes the instability of independent discharges.

Space charges of both signs are formed in the streamer channel. A non-self-sustaining discharge occurs in the pause between the pulses ($T_{pulse} - \tau_{pulse}$) in the electrode gap under the action of a separating electric field created by the constant component of the pulsating voltage U_{non}, during which ions recombine and a current is generated due to the movement of ions in the direction of electrodes of opposite polarity.

After applying the voltage pulse that caused the streamer discharge, volume charges with a density τ (the number of space charges per unit volume of the discharge gap) are formed in the discharge gap. Since a decrease in the density τ occurs in the gas volume due to the recombination and transfer of space charges, the current density through the discharge gap decreases accordingly:

$$j = ebE\tau(t),$$

where e is the electron charge, 1.6×10^{-19} C; b is the ion mobility, m^2/V·s; E is the electric field intensity, V/m; $\tau(t)$ is the time-decreasing density of volume charges, C/m^3.

Thus, the current density is proportional to the field strength in the discharge gap at the time when there are no ionization processes, i.e., conductivity is linear. The nature of the change in current density will be determined by a change in $\tau(t)$ and then, in turn, will be determined by the parameters of the electrical circuit to which the discharge gap is connected. Based on the foregoing, the process in the discharge gap in the pause between pulses can be studied by the laws of the transition process occurring in the power circuit. In this case, the discharge gap will be considered as an element of the electric circuit (Fig. 3).

According to the equivalent circuit (Fig. 4), we have a closed loop of series-forming capacitance C1, capacitance of the discharge gap C2, active R1 and inductive L resistances of the step-up transformer secondary winding, and direct resistance of the diode R2.

To determine the law of change of voltage and current of the discharge gap in the pause between pulses, we compose the characteristic circuit equation in a complex form:

$$Z = R_1 + R_2 + j\omega L + 1/(j\omega C_1) + 1/(j\omega C_2).$$

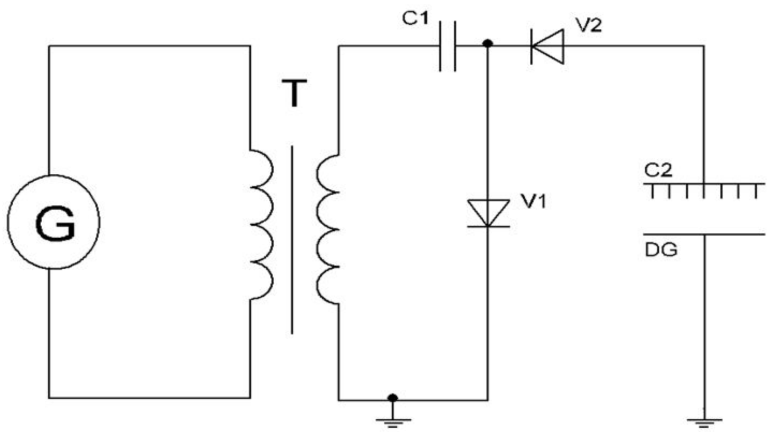

FIG. 3: Schematic diagram of the generation of unipolar high voltage pulses: G, generator of periodic voltage pulses; T, step-up transformer; C1, condenser; C2, discharge gap capacity DG; V1 and V2, diodes

If we replace the factor $j\omega$ with the operator p and the resulting expression $Z(p)$ is equal to zero, then

$$Z(p) = R_1 + R_2 + pL + 1/(pC_1) + 1/(pC_2) = 0\,,$$

or

$$p^2(C_1C_2L) + pC_1C_2(R_1 + R_2) + C_1 + C_2 = 0\,. \tag{1}$$

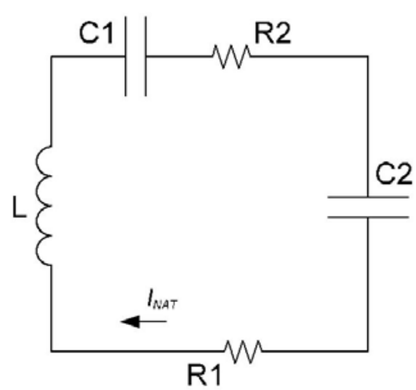

FIG. 4: The equivalent circuit of the source of high-voltage pulses in the pause between pulses: L, secondary winding inductance of the step-up transformer; C1, condenser; R1, active resistance of the secondary transformer winding; R2, direct resistance of the diode; C2, discharge gap capacity

The roots of the characteristic equation (1) are determined by the equality

$$p_{1,2} = \left\{-C_1C_2R \pm [(C_1C_2R)^2 - 4(C_1C_2L)(C_1 + C_2))]^{0.5}\right\} / (2C_1C_2L),$$

where $R = R_1 + R_2$.

Hence the free component of the voltage across the capacitor C_2:

$$U_{\mathrm{C2\,free}} = (A_1 \exp p_1t + A_2 \exp p_2t) + U_{\mathrm{a}},$$

and current in the circuit

$$i_{\mathrm{free}} = [Cd\,(U_{\mathrm{C2\,free}} - U_{\mathrm{a}})] / dt = C\,(A_1p_1 \exp p_1t + A_2p_2 \exp p_2t),$$

where $C = C_1 + C_2$.

Considering $C_1 > C_2$, we assume that the voltage U_{C1} across capacitor C_1 is equal to the amplitude of the voltage at the output of the transformer U_{a} and remains constant in the pause between pulses.

The initial conditions for calculations are

$$U_{\mathrm{C2}} = 2U_{\mathrm{a}},\ \ U_{\mathrm{C2}} = U_{\mathrm{a}},\ \ i_{\mathrm{a}} = i_0,\ \ t = 0,$$

where U_{C2} is the voltage amplitude at the discharge gap with capacity C_2; U_{a} is the voltage amplitude at the output of the step-up transformer; U_{C1} is the voltage across capacitor C_1; i_{a} is the amplitude of the discharge current; t is the integration time. Taking into consideration the accepted assumptions and the initial conditions, we obtain

$$U_{\mathrm{a}} = A_1 + A_2,\ \ i_{\mathrm{a}} = A_1p_1 + A_2p_2,$$

hereof

$$A_1 = (p_2U_{\mathrm{a}}i_{\mathrm{a}}) / (p_2 - p_1),$$

$$A_2 = (p_1U_{\mathrm{a}}i_{\mathrm{a}}) / (p_2 - p_1).$$

With these values of the integration constants, the laws of change in the voltage and current of the discharge gap in the pause between pulses are

$$U_{\mathrm{C2a}} = [1 / (p_2 - p_1)]\,[(p_2U_{\mathrm{a}} - i_{\mathrm{a}})\,p_1 \exp p_1t - (p_1U_{\mathrm{a}} - i_{\mathrm{a}})\,p_2 \exp p_2t] + U_{\mathrm{a}},$$

$$i_{\mathrm{free}} = [C / (p_2 - p_1)]\,[(p_2U_{\mathrm{a}} - i_{\mathrm{a}})\,p_1 \exp p_1t - (p_1U_{\mathrm{a}} - i_{\mathrm{a}})\,p_2 \exp p_2t].$$

The problem was solved using a PC for the following values of the circuit parameters: $L = 100$ H; $R_1 = 35 \times 10^3$ Ω; $R_2 = 2 \times 10^8$ Ω; $C_1 = 10^{-9}$, 10^{-10} F; $C_2 = 10^{-11}$, 10^{-12}; $U_a = 2 \times 10^4$ V; $i_a = 10^{-4}$ A. The integration step is 0.001 s. Based on the calculation results, voltage and current graphs of the discharge gap in the pause between pulses are highlighted in the Analysis of Results section.

4.3 High-Voltage Unipolar Pulses Generating Circuit

According to the accepted hypothesis about the combination of independent and non-independent discharges in the same discharge gap and the accepted parameters of the voltage pulse, an independent discharge occurs with intense ionization processes during the application of a voltage pulse, the amplitude of which significantly exceeds the breakdown threshold of the interelectrode gap when powered by a constant voltage. A non-self-sustained discharge occurs in the pause between pulses, characterized by the movement of the generated space charges under the influence of an electric field, the intensity of which is lower than the intensity at which an independent discharge occurs (Rakhmatov et al., 2019). From here we have two distinct processes.

A number of circuits have been elaborated to ensure high-voltage pulses generators (HVPGs), the operational principle of which is based on energy storage in reactive elements. From this there follows the definition: capacitive HVPGs, inductive HVPGs, and inductive-and-capacitive HVPGs. These VPGs belong to relaxation generators. It is conventional to divide them into dependent, restricted dependent, and independent. Relaxation HVPGs pertain to dependent ones, i.e., parameters of the pulses they produce depend on the physical state of discharge gaps. Therefore, they do not meet the above requirements and, consequently, will not ensure stability of discharge processes in the discharge technological gap. The set goal on stabilization of discharge processes can be achieved when fed from independent HVPGs, i.e., voltage pulses should be formed before their delivery to a discharge gap. The most practical way is to use circuits operating on the principle of low-voltage periodic pulse generation with further build up and rectification (Fig. 5).

Pilot research conducted during several years showed that spark high-voltage which is charged on earthed structures is not easy to avoid by taking into account the works done on pre-disruptive values of electrical field strength. Overvoltage waves are not suppressed in the fault location and can propagate along earthed

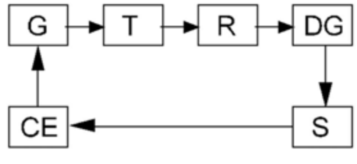

FIG. 5: Block diagram of high-voltage unipolar pulse generator: G, periodic voltage pulse generator; T, step-up transformer; R, rectifier; DG, technological discharge gap; S, discharge current inspection sensor; CE, control element

structures, causing breakdown of electrical equipment insulation at its weakpoints. As for semiconductor elements, they go out of order in trivial excess of nominal voltage they are designed for. A further study showed that the characteristics of the electric field of pulse corona discharge greatly depend on frequency. The frequency of voltage pulses and amplitude can be adjusted in the simplest way if using a machine generator of periodic voltage pulses. Therefore, the machine generator of periodic voltage pulses was used at early stages of research.

A similar feed circuit, with respect to electromechanical cotton-plant harvester, has been elaborated by He et al. (2020). Here, a machine generator with two pairs of explicit poles on rotor and stator is applied. The voltage at the generator output was in the shape of acute-angled periodic pulses (Fig. 6).

Acute-angled periodic pulses with shape factor 5 were rectified upon the build up by a rectifier assembled according to voltage-multiplying circuit without a ripple-smoothing condenser at its output. This resulted in acute-angled unipolar voltage pulses (Fig. 7) with duty cycle 5 and direct voltage component equal to $-U_n = 0.5U_a$.

The main problem of using electrical corona discharge fields in technological processes is to ensure their stability. This is obviously hard to achieve if using direct voltage. When pulsating voltage is used, the question of corona current stabilization by frequency is dropped automatically. Apparently, corona current frequency will be equal to pulse repetition frequency, provided it is short voltage pulse. The data analysis (Kostenko, 1973; Korolev and Mesyats, 1991) showed that the less the voltage-discharge gap dwell time, the higher the voltage breakdown threshold as compared to direct voltage.

4.4 Choosing the Type of Electrode System

The technology of electrical gas cleaning uses various types of corona electrodes (Levitov, 1980; Aliev, 1981, 1986): wire, needle, bayonet, spiral, etc. Based on the analysis of these works, needle electrodes, which ensure even distribution of corona points on the plane and high discharge intensity, were chosen.

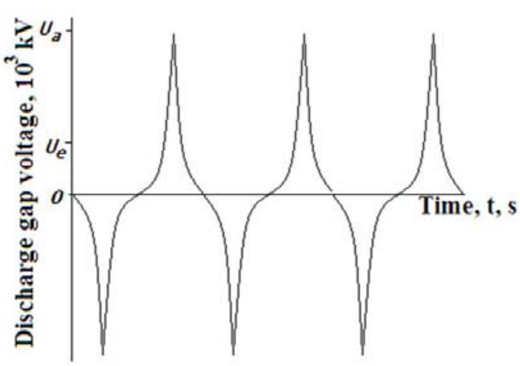

FIG. 6: A mode of output voltage of the machine generator of periodic voltage pulses

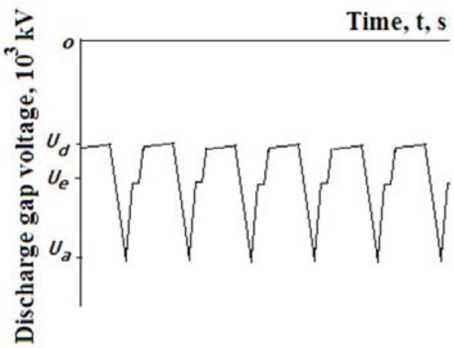

FIG. 7: A mode of output voltage of one-step-multiplier rectifier without a smoothing capacitor on the circuit output

Parameters of an adopted potential plane with corona needles–earthed plane electrode system (Fig. 8) were defined by a series of further research works. Streamer shape of corona discharge is electrically neutral, i.e., space charges (ions) of both polarities are formed at the same time. A flux of unipolar charges should be established to implement the dust precipitation process. Therefore, opposite polarity charges need to be separated. This can be done by creating a separating electric field. For this, a potential plane with corona needles installed on it can be applied and the separation process is implemented by stressing on it a direct component of voltage pulse, the magnitude of which is lower than self-maintained discharge ignition threshold (Fig. 8).

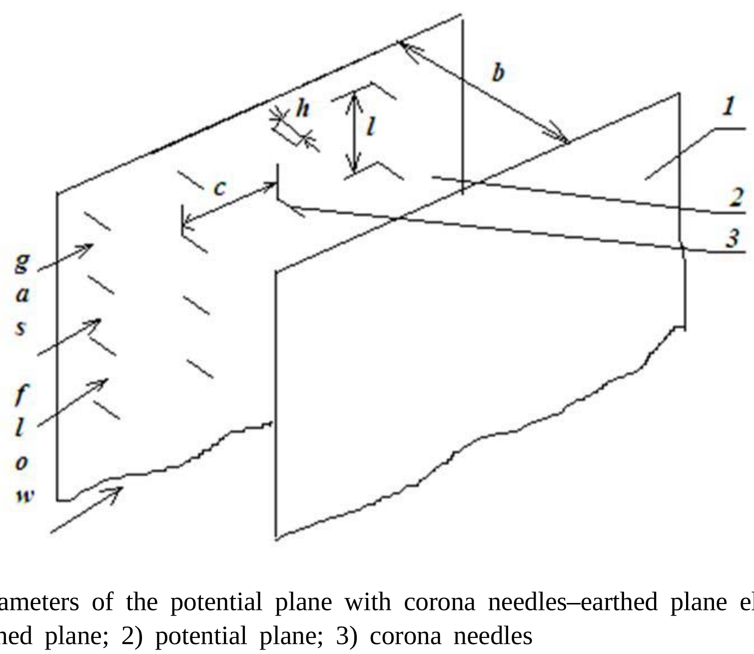

FIG. 8: Parameters of the potential plane with corona needles–earthed plane electrode system: 1) earthed plane; 2) potential plane; 3) corona needles

4.5 Choosing the Polarity of a Potential Electrode and Corona Needles

As stated in Kostenko (1973), under equal voltage amplitude, the length of positive corona streamers is far larger than that of the negative one. Consequently, under positive polarity of corona needles, spark breakdown of a technological gap will take place under a voltage less than the voltage under negative polarity. The process of dust precipitation under positive polarity of corona needles will correspondingly be much worse than if under negative polarity. This has been mentioned in the works dealing with the use of direct-voltage corona discharge in gas cleaning processes, where negative polarity of corona electrodes is also used.

Further research confirmed the competence of choosing the polarity of corona electrodes.

4.6 Analysis of Results

An analysis of curves indicates sequal alteration law $U_{C2\ nat}$ and i_{nat}. The nature of transient process depends on the circuit parameters R_1, R_2, L, C_1, and C_2, i.e., on the type of characteristic equation roots. Meanwhile, the magnitude of discharge gap capacity C_2 is determinative.

As discharge gap capacity builds up, compensation time of the charges stored in it increases. After all, as highlighted in Fig. 9, at the given capacity $C_2 = 10^{-11}$ F, the time of full charge compensation is 0.006 s, while at $C_2 = 10^{-12}$ F it is 0.001 s. Hence, the maximum pulse repetition frequency is 166 pulse^{-1} and 1000 pulse^{-1}, respectively.

The results of mathematical modeling are confirmed by a series of experimental studies. In these studies, a pulsating voltage frequency varied in the range 100–250 s^{-1}. The amplitude of the discharge current was observed up to a frequency of 200 s^{-1}. Afterward, the voltage and current of the discharge process become random.

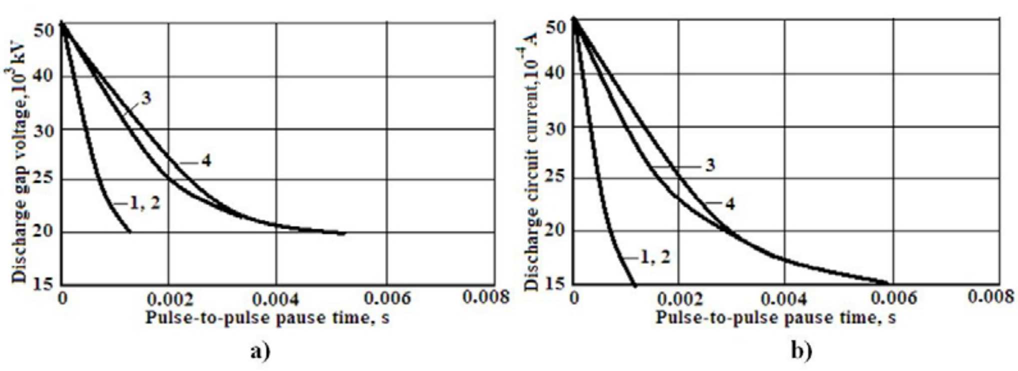

FIG. 9: Alteration process of discharge gap voltage (a) and loop current (b) during inter-pulse pause: 1) $C_1 = 10^{-10}$ F, $C_2 = 10^{-12}$ F; 2) $C_1 = 10^{-9}$ F, $C_2 = 10^{-12}$ F; 3) $C_1 = 10^{-10}$ F, $C_2 = 10^{-11}$ F; 4) $C_1 = 10^{-9}$ F, $C_2 = 10^{-11}$ F

At the same time, the force action process of the corona discharge electric field of constant and pulsating voltages was studied on the particles of the processed material. As shown in Table 1, the forces of action are 2.63 times higher in electric fields of the streamer form of a corona discharge than those in electric fields of a corona discharge of constant voltage. The dependence of electric forces on the frequency and duty cycle of pulsating voltages is also established.

The parameters of the potential plane with corona needles–earthed plane electrode system were determined experimentally by the volt–ampere characteristics of the discharge, more precisely by the inflection points (Figs. 10 and 11). The final selection of the parameters of the electrode system was carried out according to the results of studies of the process of collecting particles of dust from an air stream.

The parameters of the potential plane with corona needles–earthed plane electrode system were determined experimentally by the volt–ampere characteristics of the discharge, more precisely by the inflection points (see Table 2 and Figs. 10 and 11). It was found that the distance between the needles in the rows should be two times less than the distance between the rows of needles (see Table 3). A final selection of the electrode system parameters was carried out according to the results of studies from the process of collecting dust particles from an air stream.

To analyze the process energy intensity for collecting dust from the air stream, we adopted the parameter: the process specific power of dust deposition from the air stream, (W·s)/m^3.

The process specific power of dust deposition from the air stream was determined by the formula

$$P_s = P / G\,,\ \ (\text{W}\cdot\text{s})/\text{m}^3\,.$$

where $P = U_{\text{rms}} \cdot I$; $G = HBV$ is the booth air capacity, m^3/s; U_{rms} is the root mean square (RMS) value, V; I is the discharge current, A; H is the interelectrode distance, m; B is the stand width, m; V is the air flow rate, m/s.

For comparison, the parameters of the existing electrostatic precipitators were sampled and the process specific power was calculated (Table 4).

The specific power of the developed electrostatic precipitators is much less than that of the existing ones. It should be noted here that there is a large difference

TABLE 1: Outcomes of comparative study of powers of adhesion of trial body to the earthed plane in electric fields

Parameters	**Value of Parameters**					
Frequency of pulses						
F, H	$F = 0.62$	$F_1 = 1.11$	$F_2 = 1.21$	$F_3 = 1.37$	$F_4 = 1.63$	$F_5 = 1.44$
Q, 10^{-4} C	0.74	1.0	1.0	1.1	1.2	1.14
σ_s, 10^{-4} C/mm^2	9.48	12.6	13.2	14.1	15.3	14.4
F_n / F		1.94	2.21	2.63	2.31	1.79

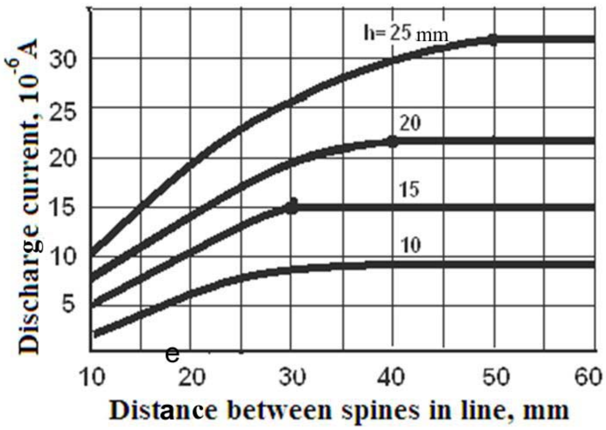

FIG. 10: Dependences of the currents of single corona needles of various lengths on the distances to neighboring corona needles at $H + h = 0.1$ m

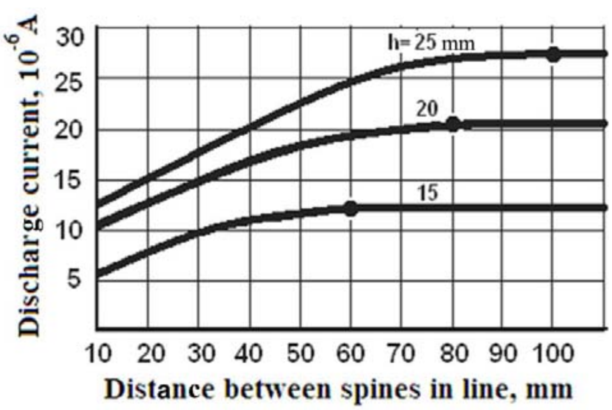

FIG. 11: Dependences of the currents of single corona needles of various lengths on the distances between the rows of corona needles at $H + h = 0.1$ m

TABLE 2: Parameters of the potential plane with corona needles–earthed grounded plane electrode system

Name of Parameter	Parameter Value		
Distance between the planes, mm	150	100	50
Needle electrode length, mm	25	20	15
Distance between the needles in a row, mm	50	40	30
Distance between the rows of needles, mm	100	80	60
Process specific power for dust collecting from the air stream, (W·s)/m^3	27	33	43.2

TABLE 3: The results of the study of dust deposition from the air stream at distances between the corona needles in rows two times greater than the distances between rows of needles (interelectrode distance 0.1 m, air flow velocity 8 m/s)

***h*, mm**	***ℓ*, mm**	***c*, mm**	***U*, 10^3·V**	***I*, 10^{-6}·A**	***f*, s^{-1}**	**Total Weight, mg**	**Degree of Purification, *W*, %**	**Degree of Purification, $W_A \pm \sigma$, %**
20	40	80	48	110	500	2682	89.4	90.4 ± 2.58
20	40	80	4	110	500	2618	87.3	
20	40	80	48	110	500	2832	94.4	
15	30	60	50	100	500	2048	68.3	71.5 ± 2.26
15	30	60	50	100	500	2190	73.1	
15	30	60	50	100	500	2192	73.1	

TABLE 4: Selection of the technical characteristics of existing electrostatic precipitators

Type of Electrostatic Precipitator	**Dimensions (length × height × width), m**	**Air Performance, m^3/s**	**Power Consumption, W**	**Specific Power, (W·s)/m^3**
EFVA 20-10	0.75 × 3 × 1.5	5.56	800	144
EFVA 40-11	0.75 × 3 × 3	11.12	1600	144
EFVA 1-08	1.3 × 0.65 × 0.6	0.28	1200	4285
EFVA 1.5-09	0.8 × 1.43 × 0.72	0.36	1200	3333
DVP-2 × 25	—	3.3	8000	242
OVP-2 × 30	—	33.8	18,000	532
PGDS 3 × 24	—	24	40,000	1667

in the specific powers of existing electrostatic precipitators with the same operation principle. Hence, significant dissociation in research and the lack of a common methodology are the main limiting factors for calculating and researching electrostatic precipitators.

5. CONCLUSIONS

1. Discharge processes in technological discharge gaps can be stabilized when the effect of self-maintained and non-self-maintained discharges overlaps. Self-maintained discharge in a streamer shape of corona discharge is formed in the discharge gap under the influence of a voltage pulse with overvoltage, while non-self-maintained is formed under the influence of pulsating voltage direct component, the magnitude of which is lower than the self-maintained discharge ignition threshold.

2. Pulsating voltage frequency, at which discharge current stability is ensured, is defined by the time of full compensation of space charges generated under the influence of voltage pulse, the parameters of feed circuit elements, and the capacity of discharge gap.
3. When fed with high-voltage unipolar pulses with overvoltage, technological discharge gaps can be viewed as an electrical circuit element.
4. According to force action process investigations of corona discharge electric fields, it is inferred that force impacts are 2.63 times higher in electric fields of a streamer form of a corona discharge than those in electric fields of a corona discharge of constant voltage. The dependence of electric forces on the frequency and duty cycle of pulsating voltage is also established.
5. A specific power of the developed electrostatic precipitators is much less than that of the existing ones.

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