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Institute of mechanics and power engineering

The department of heat power engineering systems

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MASTER'S THESIS

TESTING THE ATMOSPHERIC TYPE GAS BURNER AIR IONIZER LAYOUT

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THE TASK FOR FINAL QUALIFYING WORK

(in the form of master's thesis)

Student: Vasilev Evgeny Sergeevich

1 Theme: Testing the atmospheric type gas burner air ionizer layout.

Approved by Mordovia state University № 7882 – C from 21.09.2018 year

2 The deadline for the submission of work to the protection of 13.06.2020

3 Initial data for final qualifying work state standards, SNiPs, patent database, RD, textbook.

4 The content of the final qualifying work

4.1 Review and analysis of the effects of ionization on combustion
4.2 Theoretical background
4.3. Description of the experimental setup
4.4 Results of experimental research

Head of works	________ signature, date	21.09.2018	S. F. Kudashev initials, surname
The work has been accepted	________ signature, date	21.09.2018	E. S. Vasilev initials, surname

ABSTRACT

The master's work contains 71 pages, 23 pictures, 21 tables, 51 formulas, 44 references.

IONIZATION, BURNING, COEFFICIENT EXCESS AIR, COMBUSTION, TEMPERATURE, FACTORY EXPERIMENT, PLANNING MATRIX.

The development object is a prototype of an atmospheric gas burner air ionizer.

The purpose of the work is to determine the effect of air ionization on the efficiency of an atmospheric type burner device.

As a result of this work, the main indicators that, when changed, affect the flame combustion when ionization of air supplied to the burner were identified.

As a result of the work:

- an experimental installation was made and tests were carried out;
- a mathematical model of the experimental installation was developed;
- a regression equation that reflects the dependence of the excess air coefficient on ionization, loading and heating of air was constructed.

CONTENT

INTRODUCTION

Heat power engineering in the modern world requires the creation and implementation of new and modern solutions in production processes that will lead to an increase in the efficiency of obtaining heat energy with an equivalent economic effect.

The combustion process of fuel in heat power engineering is an integral part of obtaining a hot heat carrier. The most common type of burned organic fuel in Russia is natural gas. It, in turn, is used for a variety of technological processes in various industries, as well as premises heating. All this entails large emissions of harmful substances into the air.

Thus, focusing on the natural gas combustion is a reasonable solution that is designed to increase the efficiency of burners and reduce the amount of nitrogen oxide and carbon monoxide released into the atmosphere.

Based on the experience of the past years, it is possible to create a model and conditions under which the control of combustion processes at the molecular level will become real. When this effect is achieved, most processes that burn natural gas will become more economical and environmentally friendly.

1 General information on the influence of an external electric field on the characteristics of ignition and combustion

It was established in [1], [2] that the combustion process of various types of fuels, including natural gas, proceeds simultaneously with the ionization of molecules and the separation of positive and negative charges along the entire flame front.

Combustion is a complex process of conversion of starting materials into combustion products, proceeding both from a physical and chemical point of view, during exothermic reactions, accompanied by intense heat generation. This phenomenon is used in almost all areas of life [3].

If we consider the flame as a stationary homogeneous system, then it will not have any charge, i.e. is neutral. If we consider the flame as a laminar system, it turns out that the distribution of charges occurs unevenly. The inner cone is a region of flame with a negative charge, the outer cone is a region with a positive charge [4]. From this it is concluded that flame is an electrical system with a distributed electric charge. Therefore, if it is an electric system, then when it is exposed to an electric field, a geometric change in the direction of the flame will occur. Therefore, we can conclude that a chemical reaction occurs only at the interface of the flame front, taking into account the different speeds of unlike charges.

All this causes interest in studying the effect of an external eclectic field on the combustion process. In the case of achieving a certain efficiency, it is fair to say that this will increase the efficiency of power plants in which the application of this solution is possible and appropriate.

At present, there is a rather large base of studies of previous years, which have, in the majority, empirical data [2], [5]. Based on them, data that is obviously fair and proven to have no result will not be considered in this paper.

1.1 Problems of modern burner devices

One of the key aspects of the combustion process is mixture formation. As a rule, it is carried out in the burner, which means that the mixture formation precedes the occurrence of the flame front [6].

As it is known, the finished combustible mixture burns, but not its individual components. Its formation requires time, which will be the determining parameter of mixture formation and, therefore, will determine the speed of the process. This gives reason to consider this process as a regulator of the burning rate and becomes the principle of regulation of all main combustion processes. [7]

Until the mixture reaches the state in which it fully ignites, another stage passes, that is called primary mixture formation. The ignition front arises already at this stage, due to the fact that the fuel and oxidizer reach the minimum required temperatures for ignition, provided that the required concentration is reached. In order to accelerate the effect of increased temperature on the occurrence of the ignition front, it is necessary to limit the supply of air, which requires heating, at the initial stage (in the primary zone). Due to this, the total heat capacity of such a mixture will decrease, which means that its heating will occur faster along with the achievement of the required fuel concentration [6], [8].

All known manufactured burners, including multi-fuel ones, due to the lack of quality of mixture formation require the supply of excess air, thereby spending some of the combustion energy on its heating and significantly reducing the temperature of the torch and flue gases. The disadvantages include the fact that in case of incomplete combustion of the fuel, a significant amount of carbon monoxide, soot and other harmful volatile substances are emitted. The use of injection, swirling flows, artificial blasting and even the introduction of a pure oxidizing agent (oxygen) do not solve the problem of complete burning of fuel. This is due to the cluster nature of the gas structure. It is known that the reaction of combustion (oxidation) of fuel begins on the contact surface of clusters with oxidizer clusters and moves relatively slowly towards the center of the clusters. Theoretically, the simultaneous oxidation of fuel molecules is required. At present, the problem of the destruction of clusters to structural molecules has been partially solved [9], [10], [11] [12], [13]. In this case, the Coulomb forces with the speed of propagation of the electromagnetic wave crush and mix the combustible mixture into smaller clusters.

There are various ways to increase the efficiency of combustion processes, for example, by ionizing an oxidizing agent (air) involved in the combustion process. In the patent [12], it is proposed to ionize it before passing the oxidizing agent into the combustion zone by passing it through an electrode grid equipped with electric charge expanders. The use of the device according to this patent makes it possible to reduce fuel costs by an average of 0.5-1.5%, increase the efficiency of thermal units by 0.5-3%.

The solutions used in these patents allow a slight increase in the efficiency of combustion processes, lower fuel costs, and increase the efficiency of fuel and energy plants. However, in all these patents very complex electrode designs are offered; there are no instructions on the placement of electrodes in the furnace volume. There is no reference to the scientific research of these devices. Such designs are difficult to technically put into practice and use. Moreover, in most cases, it is proposed to conduct electric field treatment directly with a torch (flame), where temperature ionization is already deeply developed.

This goal can be achieved due to the fact that ionized air is already present in the burner region and, in the ignition start region, respectively, an ionized fuel mixture is already present, which leads to the destruction of the cluster system of vapors and gases [14].

1.2 The physical nature of the process of exposure of an external electric field to a flame

A stationary homogeneous flame is a system that has a neutral charge. However, in a flame, particles are divided into charged and uncharged, which can interact with an electric field [15].

The application of an external electric field to the flame leads to the appearance of an ordered and directed movement of ions and electrons in the combustion zone. Ions present in the flame begin to move toward oppositely charged electrodes to achieve equilibrium of the system. This phenomenon in the flame is called the ionic wind [2].

In the case of combustion of two pre-mixed environs, for example, in the case of an injection burner, in the zone of the onset of reaction formation (pre-flame reaction), which develops at the flame front, the highest concentration of positive ions is observed on the inside, and negative ions on the outside (on the front). From this condition, if a negative potential is applied to the burner, positive ions will move to the inner part of the flame, and negative ions - to the external, along the flame front at the phase boundary [16].

In the case of combustion in a laminar flame, mainly everything happens vice versa. In the zone of the onset of reaction formation, the highest concentration of positive ions is also noted, where they subsequently remain, that is, on the outer cone, and negative ions mainly move into the inner cone.

Such a separation of unlike charges is caused by different degrees of mobility of positive and negative particles. The positive ions formed during the chemical reaction have low mobility and therefore create mainly positive charges at the place of origin, and the electrons formed as a result of the same reaction have greater mobility, as a result of which they quickly leave the flame front, i.e. the reaction formation zone, and form mostly negative charges on the inner cone [17].

It is worth noting that in both cases the charged particles are distributed unevenly and have a statistical distribution.

There is a general phenomenological feature by which an unstable state of a nonequilibrium plasma differs from a stable one. It is most convenient to recognize it by referring to the equation of electron kinetics written in symbolic form [18]:

$$\frac{dn_e}{dt} = Z_+ - Z_-, \quad (1)$$

Where Z_+ - the rate of appearance of electrons;

Z_- - the rate of disappearance of electrons.

These speeds are the result of the complex kinetics of collision processes.

The steady state corresponds to equality $Z_+ = Z_-$ which satisfies the stationary state of electron density n_e. Resulting speeds Z_+, Z_- depend not only on the electron density itself n_e, but also, from other parameters:

- electronic temperature T_e;

- negative electron density n_- (if sticking occurs);

- densities of excited atoms N^* if the ionization of the latter by electron impact plays a role.

Since all these parameters on which the speeds depend Z_+, Z_- are connected by a system of differential equations, in the general case it is impossible to express the quantities Z_+, Z_- through only the electron density at a given point in time.

If the number of parameters m is counted, which describe the state of a weakly ionized molecular gas in a field: n_e, n_-, n_+ (taking into account space charges $n_+ \neq n_e + n_-$), T_e, T vibrational temperature of molecules T_v, N, N^*, E, typed ten quantities. It is clear that the analysis of the corresponding dispersion equation, even if we obtain it, presents insurmountable difficulties [19], [20].

The way out of this situation is suggested by the assessment and comparison of various parameters. In the study of a certain type of instability associated with the action of some main process and developing over time τ, usually it is possible to process “fast” processes, which take much less time than τ. In some cases, it can be processed and "slow" processes. Parameters that can be quickly established can be considered quasistationary, assuming that they “follow” the slower change in the determining parameters, instantly adjusting to their current values, as if the latter were unchanged in time. Relatively slower processes, if they exist, we can say that during the development of this instability, the corresponding parameters do not have time to change at all and remain as if “frozen” [21], [22]. The situation is completely analogous to that which takes place when considering relaxation processes leading to the establishment of thermodynamic equilibrium in various degrees of freedom of a heated gas.

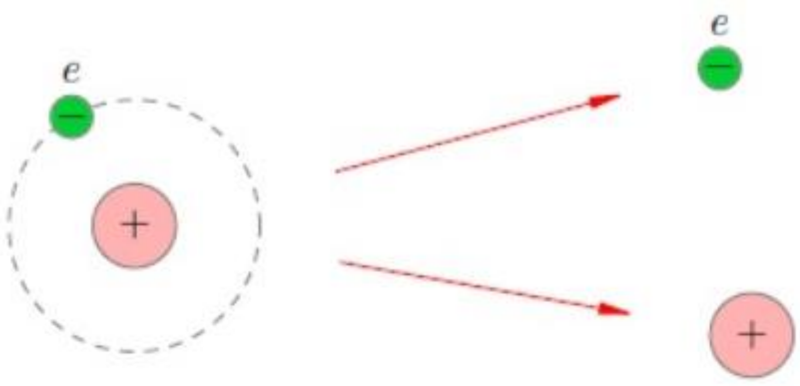
The mechanism of propagation of a combustion wave in a gaseous medium, which is associated with the process of molecular transfer, occurs as follows. The heat contained in the reaction zone due to heat transfer between the particles in contact, which plays a role at a sufficiently large temperature gradient in the boundary layer, is transferred to the reagent region. Due to this, new volumes of pre-mixed gas mixture are formed (primary mixture formation). The combustion mode in this case is kinetic, since as soon as in this mode the rate of chemical reactions depends only on the kinetics of the chemical reactions themselves. As a result of all processes, flames are formed. These are modes with the ability to self-sustain the spread of the chemical transformation zone in space. The disadvantages of this principle are:

- the inability to control the burning rate;
- problems of burning gas with preheated air;
- low flame resistance to its breakdown;
- low flame resistance to the phenomenon of slip [23].

1.3 The process of ionization in an electric field

Ionization is the process of formation of ions from neutral atoms or molecules while absorbing heat from the environment [24].

In a simple form, the ionization process is as follows (Picture 1.3.1).



Picture 1.3.1 - Ionization

The degree of ionization is the ratio of the number of ionized particles to the total number of neutral particles per unit volume. For example, an ionization degree of 30% will mean that 30% of the original particles have decayed into positive ions and electrons. It is determined by the formula:

$$S = \frac{n}{N}, \tag{2}$$

Where n - the number of ionized particles, pcs;

N is the number of neutral particles, pcs.

Since ions of both positively and negatively charged, as well as free electrons are located in a unit of conditional volume, it is necessary to understand their concentration. For this, the concept of unipolarity is introduced, which is found as:

$$S_x = \frac{n_p + n_n}{N}, \tag{3}$$

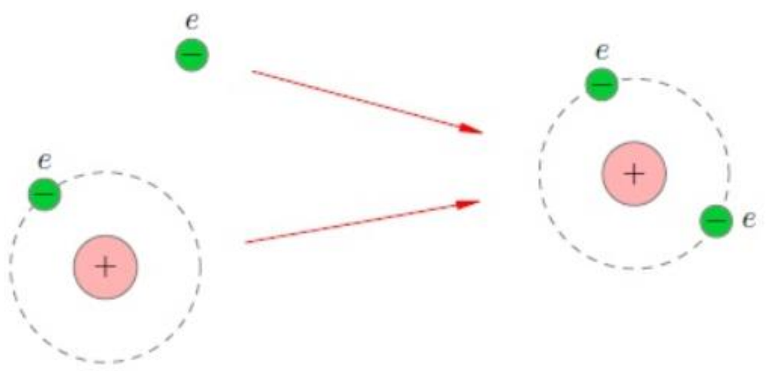
Where n_p - the number of negatively charged particles, pcs;

n_n - the number of positively charged particles, pcs;

Depending on the calculated polarity, a plus sign is determined in the case of finding the concentration of positive ions or a minus sign in the case of finding the concentration of negatively charged ions [4].

The process of formation of positively charged ions: occurs only if sufficient energy is obtained to overcome the potential barrier in an atom or electron. The potential barrier is equal to the ionization potential.

The process of formation of negatively charged ions: occurs by the formation of an additional electron, which is formed when it is captured by an atom. The process takes place with the release of energy. The final product of this reaction has more energy than individual source components. Visually, this process is presented in Picture 1.3.2.



Picture 1.3.2 - The process of formation of a negative ion

The ionization process, as a rule, requires a significant expenditure of energy. For each substance, the ionization potential is different, but they all lie in the range from 5 to 20 eV. In Table 1.3.1 the ionization potentials of the most frequently occurring particles that are involved in the combustion process are given [25].

Table 1.3.1 - Ionization Potentials

Substance	Potential, eV	Substance	Potential, eV	Substance	Potential, eV
H	13,595	Sr	5,692	CH_2	11.82 and 10.396
N	14,530	Ba	5,210	CH_3	9,905± 0,075
O	13,614	Pb	7,415	CH_4	13.06± 0.06
Ci	13,010	H_2	15,427	CH_3O	9.2
Br	11,840	OH	13.18± 0.1	C_2	12.0± 0.6
Li	5,390	H_2O	12.60± 0.01	C_2H	11.3
Na	5,138	CO	14.05± 0.05	C_2H_2	11.41± 0.02
K	4,339	O_2	12,20± 0.2	C_2H_4	10.5± 0.1
Rb	4,176	CO_2	13.84± 0.11	C_2H_6	11.65
Cs	3,893	NO	9.25± 0.02	C_2H_8	11.14± 0.07
Ca	6,111	CH	11.13± 0.22	CHO	9.88± 0.05

1.3.1 Ionization in a collision

If a particle of mass M_1 collides with a direct hit with a particle of mass M_2 at initial relative speed u_r, it can be calculated the maximum amount of kinetic energy that is converted into internal energy [26].

From the condition of conservation of momentum in the reference frame in which the particle M_2 originally movable:

$$M_1 u_r = M_1 u_1 + M_2 u_2, \tag{4}$$

i.e.:

$$u_2 = \frac{\left(M_1 u_r^2 - M_1 u_1^2\right)}{M_2}, \tag{5}$$

Where u_1 - particle velocity M_1 after the collision m/s;

u_2 - particle velocity M_2 after the collision m/s;

u_r - constant speed m/s.

The amount of kinetic energy converted into internal energy, J:

$$U = \frac{1}{2}\left(M_1 u_r - M_1 u_1\right) - M_2 u_2^2. \tag{6}$$

Substituting instead u_2 in (6) expression (5) and differentiating U by u_1 at constant speed u_r, we find the maximum condition U:

$$u_1 = u_2 = \frac{1}{2}\frac{M_1 M_2}{M_1 + M_2} u_r^2, \tag{7}$$

i.e.:

$$U_{\max} = \frac{1}{2}\frac{M_1 M_2}{M_1 + M_2} u_r^2. \tag{8}$$

In a simplified form, the chemical reaction of the two compounds will look like this:

Collision ionization:

$$A + B \to A^{+} + B + e^{-} \qquad (9)$$

$$A + e^{-} \to A^{+} + e^{-} + e^{-} \qquad (10)$$

Electron transfer:

$$A + B \to A^{+} + B^{-} \qquad (11)$$

1.4 Effects of an external electric field on the main combustion parameters

For a correct assessment of the effect of an electric field on the combustion process, it is necessary to understand how it affects the basic parameters of the process. The main parameters of the combustion process can be identified: combustion temperature and flame speed.

The value of the normal flame velocity is found from the ratio according to the theory of laminar spherical flame, m/c:

$$u_{н} = w_{f} \frac{T_0}{T^{*}}, \qquad (12)$$

Where w_f - flame propagation speed m/c,

T_0 - initial temperature $^{\circ}C$;

T^{*} - fuel combustion temperature, $^{\circ}C$.

For a deeper understanding of the process, it is necessary to understand the likelihood of a particular reaction. The probability characteristic in this case is the cross section. Thus, the collision frequency of an electron with a neutral molecule will be determined as, $1/c$:

$$v = \sigma V n_0, \tag{13}$$

Where V is the electron velocity (the true velocity in a collision with a molecule - that is, thermal at low field strengths, directed at high intensities), m/c;

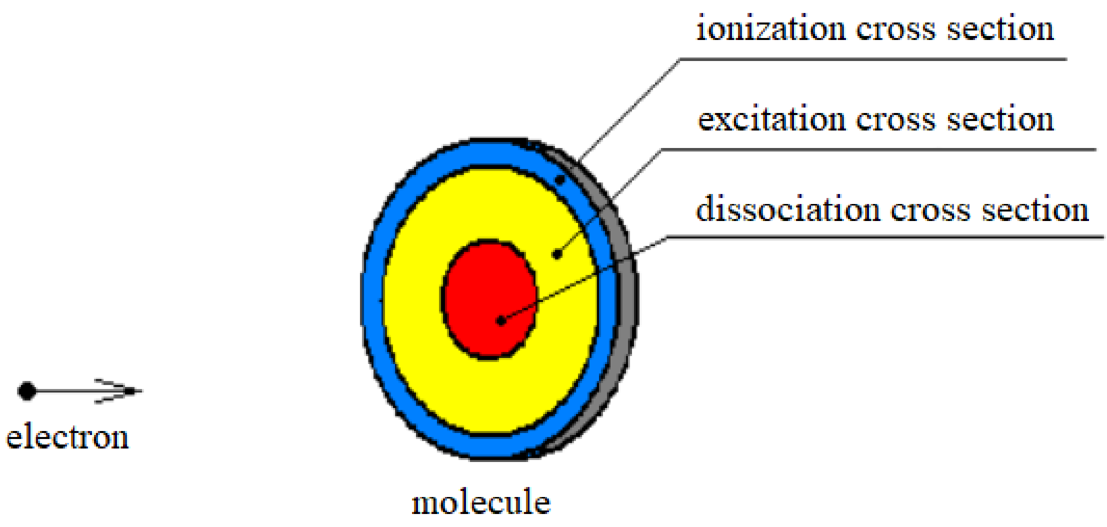
σ - cross section of the reaction, m^2;

n_0 - concentration of neutral molecules, m^{-3} .

Based on their unit size, we determine that the molecule is a ball. Collision is the contact of surfaces. In this case, the collision frequency, based on the condition that the reaction cross section will be equal to the cross-sectional area of the ball, the mean free path will be as follows, m:

$$l = \frac{1}{\sigma n_0}. \tag{14}$$

Presented in section, in Picture1.4.1, the visual component of the molecule gives a more detailed idea of the meaning of the cross section. The area of each ring corresponds to the cross section of a specific reaction, and, therefore, the larger the cross section of the reaction, the greater its probability [27], [28].



Picture1.4.1 - A visual model of the cross section of a molecule in a section with reaction rings

One of the most important parameters is the heat balance when an external electric field is applied to a burning gas-air mixture [8]. It is defined as, W :

$$Q_{pn} = ЭQ_k + Q_l = \left[Э\alpha_k \cdot F_{pn} \cdot \left(T_{pn} - T_{tn}\right)\right] + \varepsilon \cdot 5{,}67 F_{pm} \left[\left(\frac{T_{pn}}{100}\right)^4 - \left(\frac{T_{tn}}{100}\right)^4\right], \qquad (15)$$

Where Q_{pn} - released heat power from the heating surface, W. We believe that it is equal to the power supplied from the gases by electroconvection and radiation;

Q_k - emitted thermal power by convection, W;

Q_l - emitted thermal power by radiation, W;

α_k - convection heat transfer coefficient during the movement of flue gases at the heating surface without applying an electric field, $W \cdot m^2 / K$;

F_{pn} - heating surface, m^2;

T_{pn} - the average temperature of the heating surface, K;

T_{tn} - the average temperature of the coolant, K;

ε - the degree of blackness of the heating surface.

The average temperature of the heating surface is defined as K :

$$T_{pn(mn)} = \frac{T_{pn1} + T_{pn2} + T_{pn3} + ... + T_{pn(n)}}{n}, \tag{16}$$

Where n - the number of thermocouples on the heating surface, pcs.

Thermal efficiency (thermal effect of applying an electric field) is defined as, %:

$$\Delta Q = \frac{Q_{Э} - Q_{PN}}{Q_{PN}} \cdot 100, \tag{17}$$

Where $Q_{Э}$ - heat output with a field, W;

Q_{PN} - heat output without field (control), W.

The effectiveness of reducing harmful substances is defined as, %:

$$\Delta NO = \frac{NOnO - NOэ}{NOnO} \cdot 100, \tag{18}$$

$$\Delta CO = \frac{COnO + COэ}{COnO} \cdot 100, \tag{19}$$

Where $COnO$ - concentration of carbon oxides (carbon monoxide) in flue gases without imposing an electric field;

$CO_э$ concentration of carbon oxides (carbon monoxide) in flue gases in the case of an electric field;

NO_{nO} concentration of nitrogen oxides in flue gases without imposing an electric field;

$NO_э$ concentration of nitrogen oxides in flue gases in the case of an electric field.

In [8], liquid butane gas was used as fuel with the composition: isobutane - 72%, butane - 22%, propane - 6%.

The results of the experiment [8]:

- 12% reduction in gaseous fuel consumption;
- increase in the efficiency of the heat apparatus by 11.5%;
- 80% reduction in flue gas (CO) toxicity;
- reduction of nitric oxide and sulfur by 32-40%.

Based on these equations, we can conclude that an external electric field has a positive effect on the process of burning gas fuel by bringing it to a more intense, almost instantaneous mixing of oxygen and gas, which leads to an increase in intensity, and as a result, the course of the combustion process in the most complete volume, relative to a similar process without the participation of an electric field.

Another undoubted advantage is the increase in the heat transfer coefficient due to the same simultaneous combustion of fuel in the entire volume. This parameter is variable and has a spasmodic character [29]. Due to ionization, it is possible to increase the luminosity of the torch and increase heat transfer due to radiation.

The application of an external electric field makes it possible to reduce the coefficient of excess air in the combustion chamber by about 15% as mentioned in [30], and it should be noted that the coefficient of excess air is initial 1.4. This feature, together with the simultaneous combustion of fuel in full, leads to a decrease in the amount of flue gases. In proportion to this, the volume of cold air drawn in, which no longer needs additional heating, is reduced. All this allows us to conclude that the electric field increases the overall efficiency of the system.

1.5 Goals and objectives of the study

The aim of the dissertation research is to conduct experimental studies on the effect of air ionization on the combustion process in an atmospheric type burner.

The objectives of the dissertation research:

- do a comparative literature analysis of the influence of the electromagnetic field on the combustion process in atmospheric-type gas burners;
- on the basis of literature sources, analyze the mechanisms of air ionization, as well as analyze the effect of ionized air and the electromagnetic field on the combustion process;
- put a mathematical model of the process of ionization of air for combustion, based on the theory of energy chains;
- make an elementary diagram of the experimental setup for studying the effect of air ionization on the coefficient of excess air of a gas burner of atmospheric type;
- mount an experimental setup for studying the effect of air ionization on the coefficient of excess air of a gas burner of atmospheric type;
- conduct a complete factorial experiment and, on its basis, obtain a regression equation for the dependence of the coefficient of excess air on the burner load, temperature of the supplied air, voltage on the ionizer electrode.

2 Development of a mathematical model

The development of the power system requires the introduction of new economically sound and easy-to-use principles. devices and systems. Nowadays, the use of the combustion process to generate energy when burning various types of fuels plays a large role in the field of energy, metallurgy and other industries. Thus, 70% of all energy currently produced comes from burning fossil fuels. It follows that the efforts aimed at optimizing the combustion process, in order to increase its efficiency, are very relevant, and at the same time should remain at the same level, and it is better to reduce, the amount of harmful emissions from combustion products into the atmosphere.

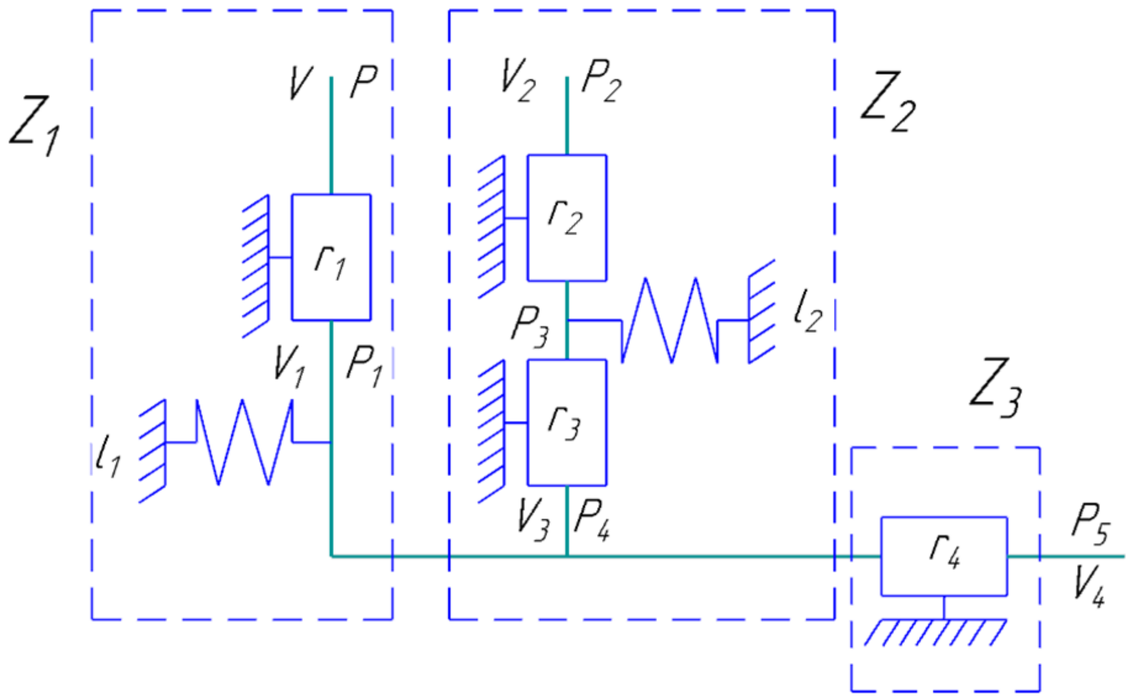
Electric charge is one of the ways to increase the enthalpy of combustion products of various types of fuels. Based on the study of the peculiarities of the influence of electric fields on combustion, it is possible to create new methods of controlling combustion processes in power and technological installations that reduce fuel consumption, reduce harmful emissions into the atmosphere and intensify the combustion process [31].

In order to increase the efficiency of gas combustion and reduce the size of the thermal units of the equipment, it is proposed to burn gas in the form of an ionized mixture by acting on it with an electric field. In this case, instantly in the entire volume at any point of the furnace, Coulomb repulsive forces begin to act, destroying the cluster structure of the combustible mixture. Due to intense mixing, the process of simultaneous burning of the torch, a significant increase in temperature, and its luminosity increase.

The heating of the working surface already occurs to a greater extent due to radiation in the infrared, visible and ultraviolet spectrum than by convective means from hot gases. The amount of carbon monoxide is reduced.

2.1 Ionization

The processes taking place, in the circuit with the ionizer, are considered using the theory of chains. The energy circuit of one circuit, consisting of three links, is presented in Picture 2.1:



Picture 2.1 - The energy chain of three links

The equation of the chain links:

$$Z1)\begin{cases} P = r_1 V^2 + P_1 \\ V = l_1 \dot{P}_1 + V_1 \end{cases}, \qquad (20)$$

$$Z2)\begin{cases} P_2 = r_2 V_2^2 + r_3 V_3^2 + P_4 \\ V_2 = l_2 \dot{P}_3 + V_3 \end{cases}. \qquad (21)$$

We make calculations for Z1.

Equation on P:

$$P = r_1\left[V_{10}^2 + 2V_{10}\left(l_1\dot{\bar{P}}_1 + \bar{V}_1\right)\right] + P_{10} + \bar{P}. \tag{22}$$

Equation on V:

$$V = l_1\dot{\bar{P}}_1 + V_{10} + \bar{V}_1, \tag{23}$$

$$P = 2V_{10}\bar{V}_1 + r_1V_{10}^2 + 2V_{10}l_1\dot{\bar{P}}_1 + \bar{P}_1 + P_{10}. \tag{24}$$

We introduce the coefficients:

$$a_1 = 2V_{10},$$

$$a_2 = r_1V_{10}^2,$$

$$b_1 = 2V_{10}l_1,$$

$$b_2 = 1,$$

$$b_3 = P_{10}.$$

Equation on P taking into account the coefficients has the following form:

$$P = a_1\bar{V}_1 + a_2 + b_1\dot{\bar{P}}_1 + b_2\bar{P}_1 + b_3. \tag{25}$$

Applying the Laplace transform, we obtain the equation for the image:

$$(a_1 + 1)V_1(s) = -(b_1P + b_2 + 1)P_1(s). \tag{26}$$

Integrated circuit resistance:

$$Z_1(p)=\frac{P_1(p)}{V_1(p)}=-\frac{a_1+1}{(b_1P+b_2+1)}, \tag{27}$$

After substituting the entered coefficients:

$$Z_1(p)=\frac{P_1(p)}{V_1(p)}=-\frac{21}{(0,04P+2)}. \tag{28}$$

We make calculations for Z1.

Equation on P_3:

$$P_3=r_3V_3^2+P_4,$$

$$\dot{P}_3=2r_3V_{30}\dot{\bar{V}}_3+\bar{P}_4,$$

$$V_2=V_{30}+\left(2l_2r_3V_{30}\dot{\bar{V}}_3+l_2\bar{P}_4+\bar{V}_3\right). \tag{29}$$

Equation on V_2:

$$V_2^2=V_{30}^2+2\left(2l_2r_3V_{30}\dot{\bar{V}}_3+l_2\bar{P}_4+\bar{V}_3\right)V_{30}. \tag{30}$$

Equation on P_2:

$$P_2=r_2V_{30}^2+4r_2r_3l_2V_{30}^2\dot{\bar{V}}_3+2l_2V_{30}\bar{P}_4V_2+2V_{30}\bar{V}_3r_2+r_3V_{30}^2+2r_3V_{30}\bar{V}_3+P_{40}+\bar{P}_4,$$

$$P_2 = 4r_2r_3l_2V_{30}^2\dot{\bar{V}}_3 + \left(2r_2V_{30} + 2r_3V_{30}\right)\bar{V}_3 + \left(r_2r_3\right)V_{30}^2 + \left(2l_2r_2V_{30}\right)\bar{P}_4 + P_{40}. \quad (31)$$

We introduce the coefficients:

$$a_1 = 4r_2r_3l_2V_{30}^2,$$

$$a_2 = 2r_2V_{30} + 2r_3V_{30},$$

$$a_3 = (r_2r_3)V_{30}^2,$$

$$b_1 = 2l_2r_2V_{30},$$

$$b_2 = P_{40}.$$

Equation on P_2 taking into account the coefficients has the following form:

$$P_2 = a_1\dot{\bar{V}}_3 + a_2\bar{V}_3 + a_3 + b_1\bar{P}_4 + b_2. \quad (32)$$

Applying the Laplace transform, we obtain the equation for the image:

$$(a_1P + a_2 + 1)V_1(s) = -(b_1 + 1)P_1(s). \quad (33)$$

Integrated circuit resistance:

$$Z_1(p) = \frac{P_4(p)}{V_3(p)} = -\frac{a_1P + a_2 + 1}{(b_1 + 1)}. \quad (34)$$

After substituting the entered coefficients:

$$Z_1(p) = \frac{P_4(p)}{V_3(p)} = -\frac{69{,}12P + 265}{1{,}48}. \quad (35)$$

Joint system solution:

$$Z_{1-2}=\frac{Z_1Z_2}{Z_1+Z_2}=\frac{\dfrac{a_1+1}{(b_1P+b_2+1)}\cdot\dfrac{a_1P+a_2+1}{(b_1+1)}}{\dfrac{a_1+1}{(b_1P+b_2+1)}+\dfrac{a_1P+a_2+1}{(b_1+1)}}, \quad (36)$$

$$Z_{\sum}=Z_{1-2}+r_4=\frac{\dfrac{a_1+1}{(b_1P+b_2+1)}\cdot\dfrac{a_1P+a_2+1}{(b_1+1)}}{\dfrac{a_1+1}{(b_1P+b_2+1)}+\dfrac{a_1P+a_2+1}{(b_1+1)}}+r_4 \quad (37)$$

$$Z_{\sum}=\frac{\dfrac{(a_1+1)(a_1P+a_2+1)}{(b_1P+b_2+1)(b_1+1)}}{\dfrac{(a_1+1)(b_1+1)+(a_1P+a_2+1)(b_1P+b_2+1)}{(b_1P+b_2+1)(b_1+1)}}+r_4=$$

$$=\frac{a_1^2P+a_1a_2+a_1+a_1P+a_2+1}{a_1b_1+a_1+b_1+1+a_1b_1P^2+a_1b_2P+a_1P+a_2b_1P+a_2b_2+a_2+b_1P+b_2+1}+r_4=$$

$$=\frac{\left(a_1^2+a_1\right)P+\left(a_1a_2+a_1+a_2+1\right)}{a_1b_1P^2+\left(a_1b_2+a_1+a_2b_1+b_1\right)P+\left(a_1b_1+a_1+b_1+a_2b_2+a_2+b_2+2\right)}+r_4=$$

$$=\frac{-525P-2012{,}8}{P^2+53{,}8339P+202{,}937}+8. \quad (38)$$

Frequency circuit function:

$$Z(j\Omega)=\frac{\left(a_1^2+a_1\right)j\Omega+\left(a_1a_2+a_1+a_2+1\right)}{-a_1b_1\Omega^2+\left(a_1b_2+a_1+a_2b_1+b_1\right)j\Omega+\left(a_1b_1+a_1+b_1+a_2b_2+a_2+b_2+2\right)}+r_4=$$

$$=\frac{-525j\Omega-2012{,}8}{-\Omega^2+53{,}8339j\Omega+202{,}937}+8. \quad (39)$$

The real part of the frequency function:

$$\operatorname{Re}(j\Omega) = \frac{-2012,8}{-\Omega^2 + 202,937} + 8. \tag{40}$$

The imaginary part of the frequency function:

$$Im(j\Omega) = \frac{-525\Omega}{53,8339\Omega} j + 8. \tag{41}$$

Frequency response of a circuit:

$$A(j\Omega) = \sqrt{\operatorname{Re}^2(j\Omega) + Im^2(j\Omega)}. \tag{42}$$

Phase-frequency characteristic of the circuit:

$$\varphi(j\Omega) = -arctg\frac{Im(j\Omega)}{\operatorname{Re}(j\Omega)}. \tag{43}$$

Table 2.1.1 - the source data of the circuit

r_1	r_2	r_3	r_4	l_1	l_2	V_{10}	V_{30}	P_{10}	P_{30}
4	5	6	8	0,002	0,004	10	12	100	200

Table 2.1.2 - Values of the entered coefficients Z_1

a_1	a_2	b_1	b_2	b_3
20	40,000	0,04	1	100

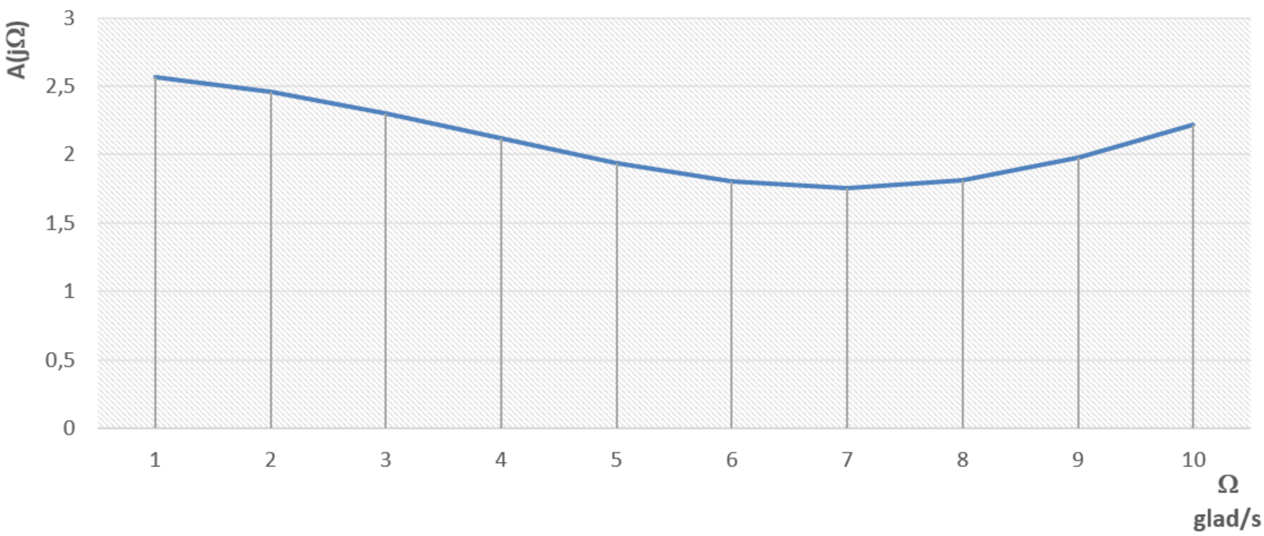
Table 2.1.3 - Values of the entered coefficients Z_2

a_1	a_2	a_3	b_1	b_2
69,12	264	4320	0,48	200

Table 2.1.4 - Received data $Z_{\sum}$

Ω	Re	Im	*A*	*φ*
1	-1,869714667	-1,752219326	2,562441317	-0,75296959
2	-1,726631777	-1,752219326	2,459985744	-0,792753203
3	-1,497161892	-1,752219326	2,304726947	-0,863731703
4	-1,193512289	-1,752219326	2,120081166	-0,972838352
5	-0,830510185	-1,752219326	1,939077032	-1,128183685
6	-0,423977869	-1,752219326	1,802783903	-1,333393053
7	0,010701088	-1,752219326	1,752252003	1,56468924
8	0,459644036	-1,752219326	1,811503577	1,314255406
9	0,911103519	-1,752219326	1,974938528	1,091299735
10	1,355714224	-1,752219326	2,215453368	0,912291052

We construct the amplitude-frequency characteristic (AFC) and phase-frequency characteristic (PFC) of the circuit.



Picture 2.1.1 - Frequency response of a circuit

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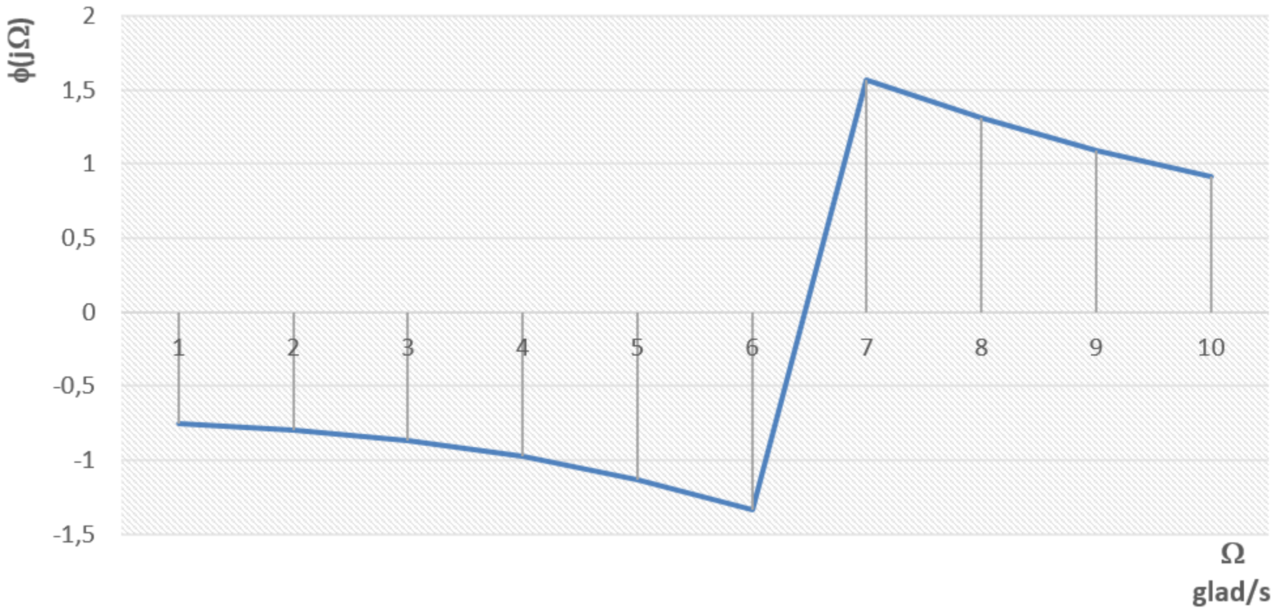


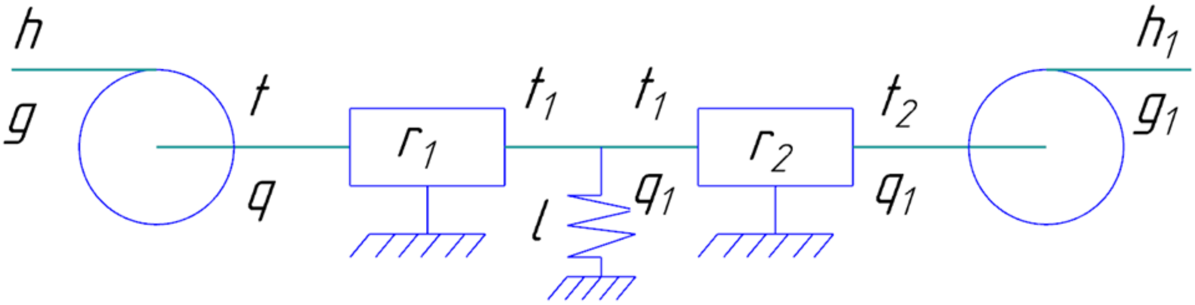
Picture 2.1.2 - Phase-frequency characteristic of the circuit

The frequency response graph has a clearly defined minimum, which corresponds to a frequency of 7 rad / s, which is the most optimal for the ionization process under consideration.

The phase response curve has two clearly defined inflection points of the function: maximum and minimum in the frequency range from 6 to 7 radian per second.

2.2 Heat transfer

A diagram of the energy chain is drawn:



Picture 2.2.1 - Energy circuit for heat transfer

The equation of the chain links:

$$\begin{cases} t = r_1 q + r_2 q_1 + t_2 \\ q = l\dot{t}_1 + q_1 \end{cases}, \tag{44}$$

$$\begin{cases} t_2 = t_{20} + \bar{t}_2 \\ q_1 = q_{10} + \bar{q}_1 \end{cases}. \tag{45}$$

The increment equation:

$$t_1 = r_2 q_1 + t_2,$$

$$\dot{t}_1 = r_2 \dot{\bar{q}}_1 + \dot{\bar{t}}_2. \tag{46}$$

Equation on q:

$$q = l\dot{t}_1 + q_1 = l r_2 \dot{\bar{q}}_1 + l\dot{\bar{t}}_2 + q_{10} + \bar{q}_1 = l\dot{\bar{t}}_2 + l r_2 \dot{\bar{q}}_1 + \bar{q}_1 + q_{10}. \tag{47}$$

We introduce the coefficients:

$$a_1 = l\,,$$

$$b_1 = lr_2\,,$$

$$b_2 = 1\,,$$

$$b_3 = q_{10}\,.$$

Equation on P taking into account the coefficients has the following form:

$$P = a_1\dot{\bar{t}}_2 + b_1\dot{\bar{q}}_1 + b_2\bar{q}_1 + b_3\,. \tag{48}$$

Applying the Laplace transform, we obtain the equation for the image:

$$(a_1P)t_2(p) = -(b_1P + b_2 + 1)q_1(p)\,. \tag{49}$$

Integrated circuit resistance:

$$Z(p) = \frac{t_2(p)}{q_1(p)} = -\frac{b_1P + b_2 + 1}{a_1P}\,. \tag{50}$$

Frequency circuit function:

$$Z(j\Omega) = -\frac{b_1 j\Omega + b_2 + 1}{a_1 j\Omega} = -\frac{b_1\Omega + (b_2 + 1)\,j}{a_1\Omega}\,. \tag{51}$$

The real part of the frequency function:

$$\mathrm{Re}(j\Omega) = -\frac{b_1\Omega}{a_1\Omega}\,. \tag{52}$$

The imaginary part of the frequency function:

$$Im(j\Omega) = \frac{b_2 + 1}{a_1 \Omega} j. \tag{53}$$

Frequency response of a circuit:

$$A(j\Omega) = \sqrt{\mathrm{Re}^2(j\Omega) + Im^2(j\Omega)}. \tag{54}$$

Phase-frequency characteristic of the circuit:

$$\varphi(j\Omega) = -arctg\frac{Im(j\Omega)}{\mathrm{Re}(j\Omega)}. \tag{55}$$

Table 2.2.1 - the source data of the circuit

n/n	r_2	l	q_{10}
1	10	50	500
2	5	70	200
3	20	20	900

Table 2.2.2 - Values of the entered coefficients Z_1

n/n	a_1	b_1	b_2	b_3
1	50	500	1	500
2	70	350	1	200
3	20	400	1	900

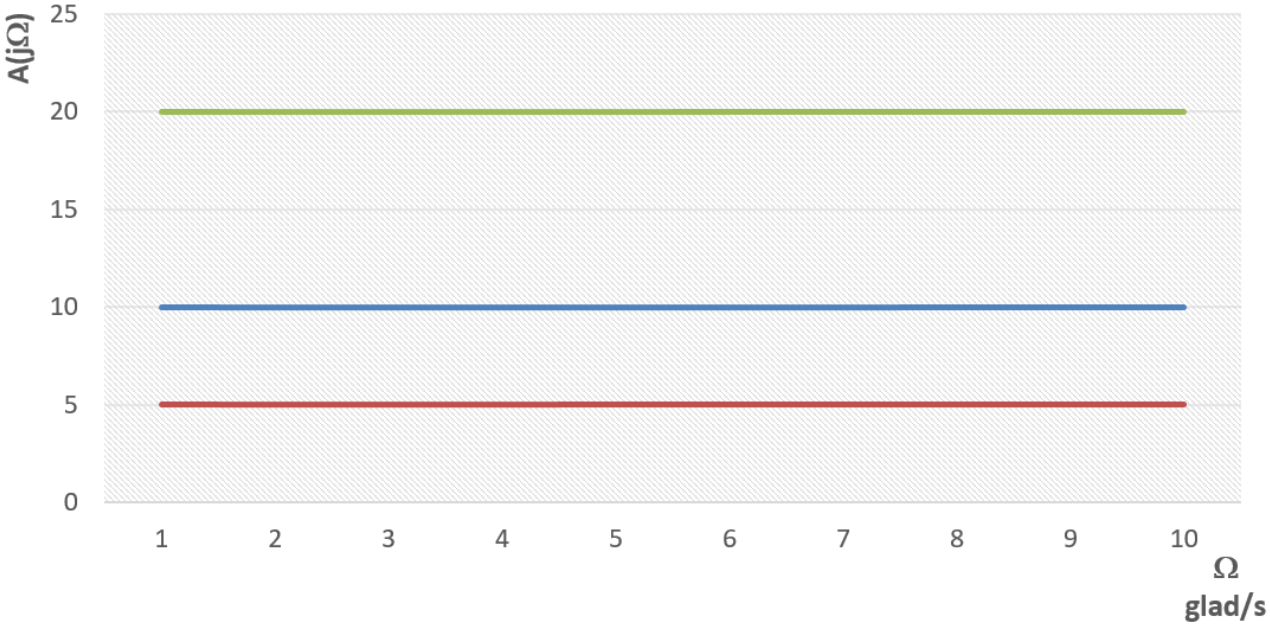
Table 2.2.3 - Received data Z_1

Ω	Re	Im	A	φ
1	-10	0,04	10,00008	0,003999979
2	-10	0,02	10,00002	0,001999997
3	-10	0,013	10,00000889	0,001333333
4	-10	0,01	10,000005	0,001

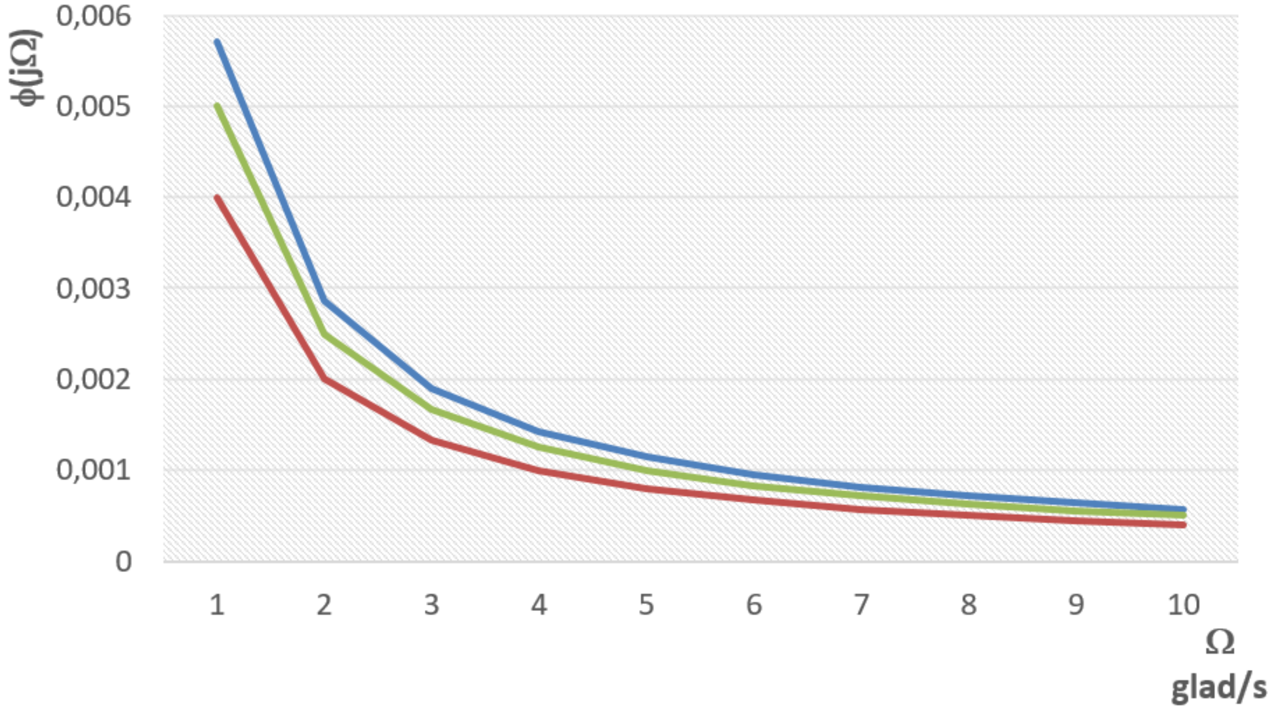
End of table 2.2.3

5	-10	0,008	10,0000032	0,0008
6	-10	0,0067	10,00000222	0,000666667
7	-10	0,0057	10,00000163	0,000571429
8	-10	0,005	10,00000125	0,0005
9	-10	0,004	10,00000099	0,000444444
10	-10	0,004	10,0000008	0,0004

We construct the amplitude-frequency characteristic (AFC) and phase-frequency characteristic (PFC) of the circuit.



Picture 2.2.1 - Chart response of a circuit



Picture 2.2.2 - Phase-frequency characteristic of the circuit

3 Experimental unit

In order to increase the efficiency of burning natural gas, compared with traditional methods, and to improve burner devices without making a big change in the design, it is proposed to burn natural gas in the form of an ionized gas-air mixture. This process is carried out due to the influence of an external electric field on the flame, or due to the preliminary ionization of the air supplied to the nozzle.

Regardless of the chosen ionization method, the Coulomb repulsive forces begin to act in the entire volume of the flame, or rather, at each of its points. Due to this, intense mixing of the gas-air mixture occurs [32], [33].

This leads to two key factors [34]:

- the amount of carbon monoxide (CO) at the outlet is reduced;
- increased heating of the working surface due to simultaneous radiation in the infrared, visible and ultraviolet spectra.

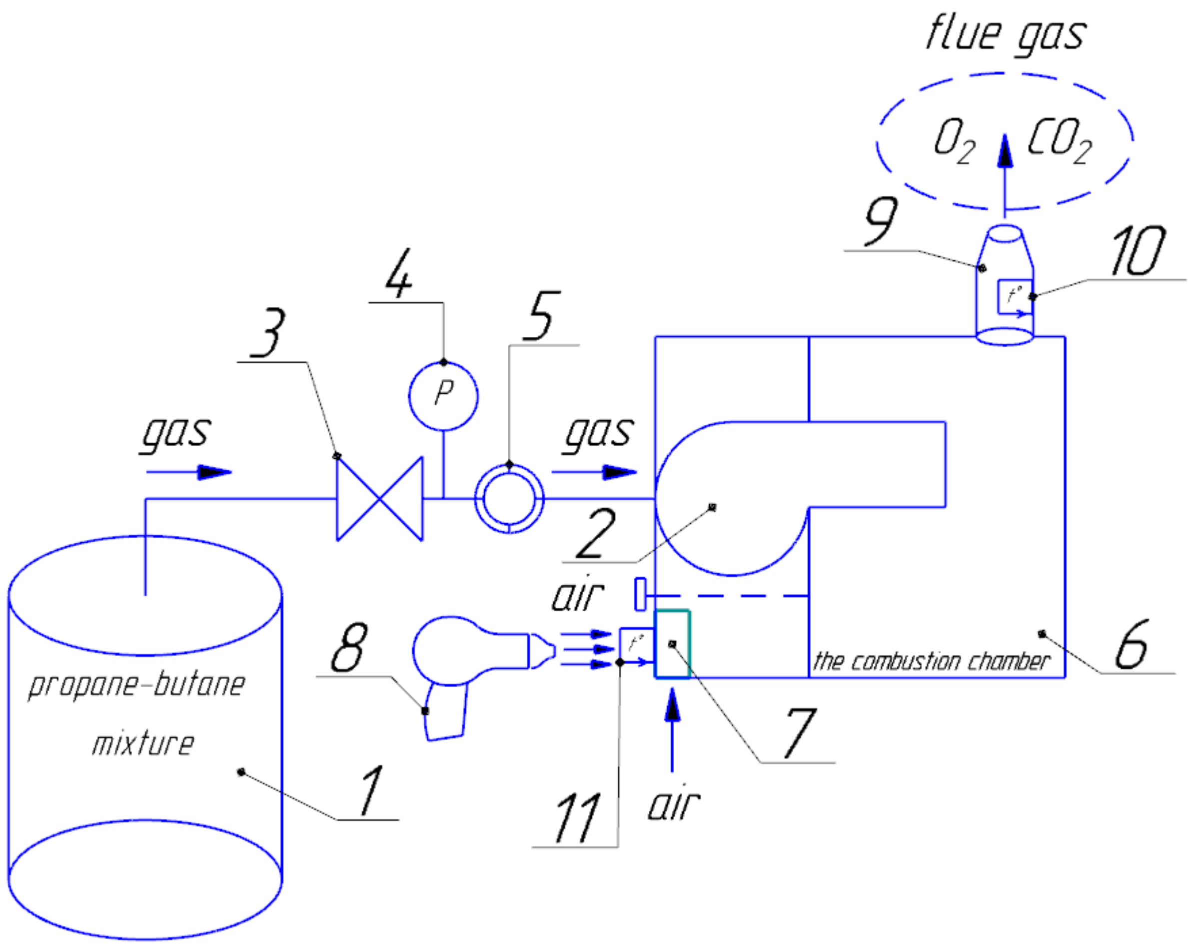
Moreover, during ionization, the luminosity of the flame is enhanced due to the burning of the flame and a simultaneous increase in temperature against this background [35].

The novelty of this work is that we propose to burn the gas-air mixture not in a standard way, but with preliminary ionization of the air, which will participate in the mixture formation and subsequent combustion. The option of applying an electric field to the flame is not considered due to the fact that this method has limitations on use, and therefore cannot be applied in some cases. The conditions under which pre-ionized air will be involved in the process of mixing are much easier to create, which is the reason for the choice.

3.1 Schematic diagram of the experimental setup

The schematic diagram of the installation is shown in Picture 3.1.1. which includes 11 positions: gas cylinder 1, atmospheric type injection burner 2, pressure reducer 3, pressure gauge 4, gas flow meter 5, combustion chamber 6, air ionizer 7, industrial dryer 8, chimney 9, temperature sensors 10, 11.

The processes in the circuit are as follows. From a gas cylinder 1 through a flexible connection, natural gas (propane) is supplied to an atmospheric-type injection burner 2. A pressure reducer 3 with a pressure gauge 4 and a gas flow meter 5 are installed on the gas line to control the pressure of the gas mixture at the outlet of the cylinder 1 to operating pressure necessary for the correct operation of the gas burner 2 and its maintenance, regardless of the pressure in the cylinder 1 and the gas pipeline. Air is supplied to the combustion chamber 6 through an air ionizer 7 to ensure that only ionized air is supplied to the burner 2. Thanks to the industrial hairdryer 8, it is possible to control the temperature of the supplied air to the ionizer 7. When the gas-air mixture is burned in the combustion chamber 6, the exhaust gases with a reduced amount of carbon monoxide, passing through the chimney 9 are removed from the combustion chamber. Temperature sensors 10 and 11 record the temperatures in front of the ionizer 7 and in the chimney 9, respectively.



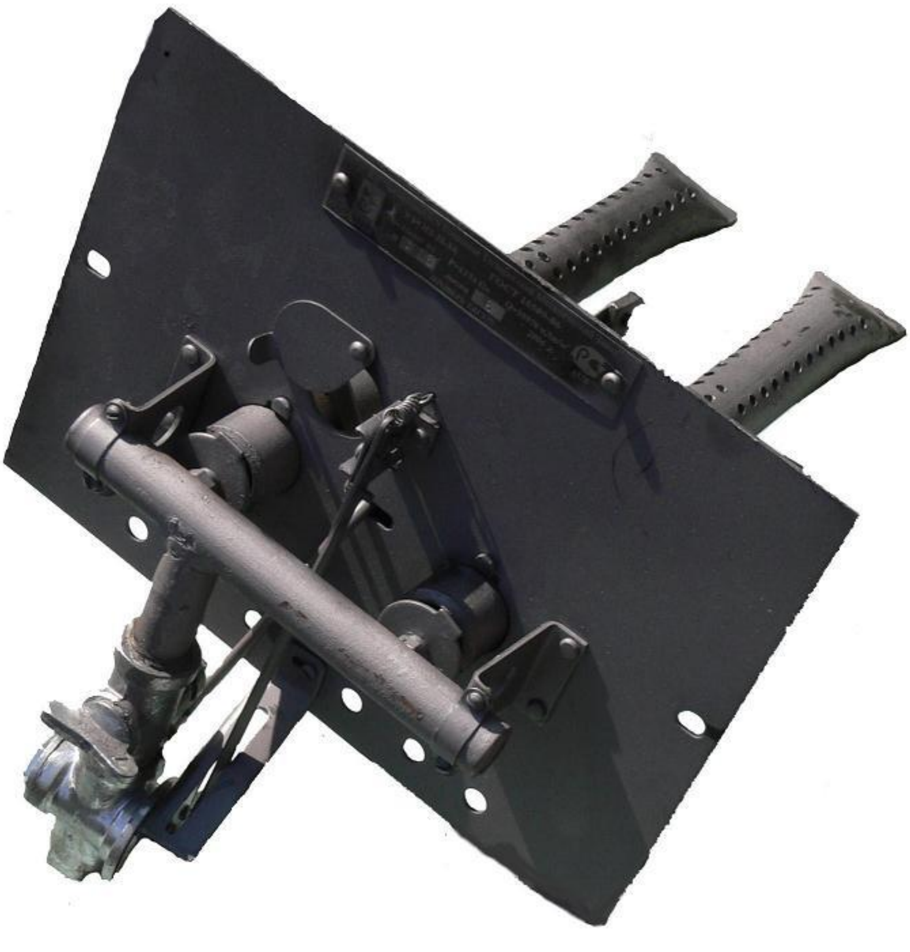
1 - gas cylinder; 2 - gas burner; 3 - pressure reducer; 4 - pressure gauge; 5 - gas flow meter; 6 - a combustion chamber; 7 - air ionizer; 8 - industrial dryer; 9 - chimney; 10, 11 - temperature sensors.

Picture 3.1.1 - Schematic diagram of the experimental setup

3.2 Equipment selection

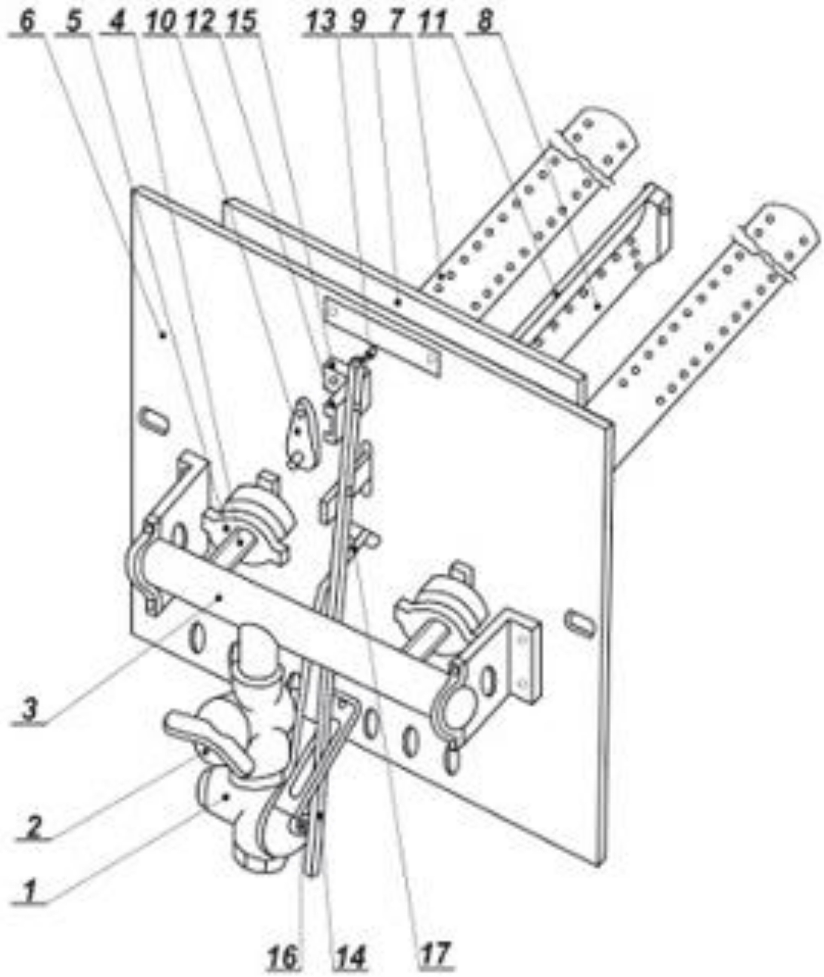
3.2.1 Gas injection torch UG-16

The gas injection torch UG-16 is made according to GOST 16569-86 and is intended for heating furnaces. It is made of steel pipes in which equidistant technological holes are made to allow uniform distribution of the flame throughout the furnace volume. As a result, the design of the burner provides the declared passport data on power with the optimal amount of heat received. The appearance of this burner is shown in Picture 3.2.1.1.



Picture 3.2.1.1 - Appearance of an injection torch UG-16

Variable nozzle throughput ensures stable flame burning without forced air supply to the burner, which in turn ensures complete combustion of natural gas. More deliberately, the burner, as one of the most important components, is represented schematically in Picture 3.2.1.2.



1– valve; 2 - crane; 3 - gas distributor; 4 - nozzle; 5 - gas supply regulator; 6 - frontal shield; 7 - main burner; 8 - ignition burner; 9 - reflector; 10 - inspection damper; 11 - temperature sensor with a fixing screw; 12 - node mounting lever; 13 - spring; 14 - lever; 15 - bracket; 16 - valve button; 17 - gas pipeline ignition burner;

Picture 3.2.1.2 - Gas injection torch UG-16 in isometry

Technical characteristics are presented in table 3.2.1.

Table 3.2.1 - Technical characteristics of UG-16

Parameter Name	Values
Rated thermal power kW	16
Thermal power, kW	12
Nominal working gas pressure in the network, Pa	1274 or 1960
Heating area m^2	Up to 120
Fuel consumption, m^3 / h	No more than 1,8
Gas pressure mb	13
Du connection for gas supply, mm	15
Dimensions, mm	300x340x415
Weight, kg	6

3.2.2 Gas cylinder

A gas cylinder is a vessel operating under excessive internal pressure. It is designed to transport and store industrial gases such as propane (C_3H_8), butane (C_4H_{10}) and mixtures thereof. This gas cylinder is welded and consists of a shell, bottom and neck. It is made of steel that can withstand internal and external loads, while not violating the original properties of the technical gases that are in it. In accordance with GOST 949-73 has a red color and a white inscription. In accordance with safety rules and operating rules, a valve VB-2 and a valve KB-2 are installed on it. The appearance of the gas cylinder is shown in Picture 3.2.2.

Picture 3.2.2 - Gas cylinder NZGA 27 liters

Technical characteristics of this cylinder are presented in table 3.2.2.

Table 3.2.2- Technical characteristics of the gas cylinder NZGA

Parameter Name	Values
Gas type	propane
A type	welded
Volume l	27
Material	high alloy steel
Operating pressure, MPa	2,5

End of table 3.2.2

Dimensions, *mm*	600x280x280
Weight, *kg*	12

3.2.3 Digital thermometer

A digital thermometer is a device for measuring temperature. As a thermosensitive element, external temperature sensors are used - resistance thermocouples. The main component of this thermometer is an analog-to-digital converter, which operates on the principle of modulation, that is, the conversion of one or more (up to 4) information signals of the converter in accordance with the instantaneous values of information signals from sensors. The power supply is due to the stable voltage by including a 9 V battery in the circuit. The appearance of the digital thermometer is shown in Picture 3.2.3.

Picture 3.2.3 - Digital thermometer 2D02

Technical characteristics of this thermometer are presented in table 3.2.3.

Table 3.2.3 - Technical characteristics of a digital thermometer 2D02

Parameter Name	Values
Connection form	K-type
Number of channels *pcs*	4
Measuring range °*C*	-50 to +1350
Accuracy of measurements, °*C*	± 0.015% + 1
Working humidity%	10-90
Material	ABS plastic
Probe length *m*	0,95
Number of probe sensors *pcs*	4
Power Supply, V	9
Dimensions, *mm*	170x100x46
Weight, *kg*	0,23

3.2.4 Propane reducer BPO-5M

Propane gearbox is a device designed to control, maintain and create the necessary pressure coming from a power source (gas bottle). The reducer joins a cylinder with a union nut. When the adjustment screw is rotated clockwise, the force of the compression spring is transmitted through the pressure plate, diaphragm and pusher to the pressure reducing valve, which, moving, opens the gas passage through the gap formed between the valve and the seat into the working chamber. Existence of the manometer provides control of pressure in the chamber of working pressure. The appearance of the propane gearbox is shown in Picture 3.2.4.

Picture 3.2.4 - BPO-5M propane gearbox

Technical characteristics of this gearbox are presented in table 3.2.4.

Table 3.2.4 - Technical characteristics of the propane gearbox BPO-5M

Parameter Name	Values
Max working pressure *MPa*	0,3
Max bandwidth m^3 / h	5
Inlet pressure bar	25
Gas type	propane
Material	brass
Dimensions, *mm*	145x138x94
Weight, *kg*	0,43

3.2.5 Gas meter SGBM-1.6 BETAR

Small-sized gas meters SBGB are designed to measure gas volume when taking into account gas consumption by individual consumers in housing and communal services. The Betar SGBM-1.6 gas meter has an electronic display that shows the amount of gas used. The meter is powered by a built-in lithium battery.

The appearance of the counter is shown in Picture 3.2.5.

Picture 3.2.5 - Gas meter SGBM-1.6 BETAR

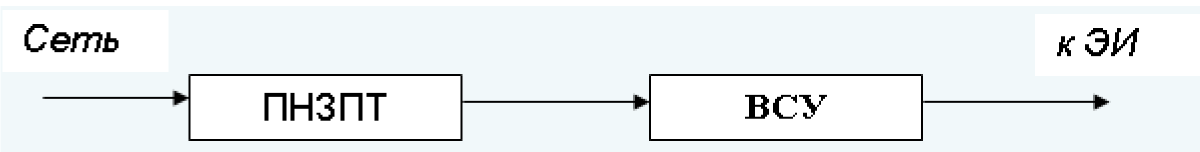
Technical characteristics of this counter are presented in table 3.2.5.

Table 3.2.5 - Technical characteristics of the gas meter SGBM-1.6 BETAR

Parameter Name	Values
Air consumption, m^3 / h	1,6
Measurement range, m^3 / h	0,04 ... 1,6
Max working pressure kPa	5
Temperature range $°C$	-10 ... 50
Material	steel
Dimensions, mm	70x88x76
Weight, kg	0,67

3.2.6 Ionizer

An air ionizer is a device designed to enrich air with negative ions. It works on the basis of the electroeffluvial aeroionization method discovered by Professor A. L. Chizhevsky. Working bodies - high-voltage voltage generator (GVN). The operation diagram of the high voltage generator is shown in Picture 3.2.6.1. Electroeffluvial emitter (EI)



PNZPT - voltage converter with a DC link; APU - rectifier - matching device.

Picture 3.2.6.1 - block diagram of the GVN

The ionizer works as follows: when the ionizer is connected to the network 220 V with a frequency of 50 Hz, PNZPT is converted into a sequence of high-voltage pulse voltages of increased frequency and, according to Picture 3.2.6.1, is fed to a rectifier-matching device (APU). From the output of the APU, a constant negative voltage, which is necessary for the effective operation of the ionizer, is supplied to the electro-effusive emitter (EI). As a result of this, electrons flow into the air, which, when combined with oxygen molecules, then form negatively charged oxygen ions. They are under the influence of a constant electric field equidistant from the source in all directions. Due to this, the air mass is filled with negative air ions. Electric charges flow from all dead-end surfaces to all grounded objects.

The appearance of the ionizer is shown in Picture 3.2.6.2.

Picture 3.2.6.2– Appearance of an air ionizer

Technical characteristics of this ionizer are presented in table 3.2.6.

Table 3.2.6- Technical characteristics of the Effluvion-02 air ionizer

Parameter Name	Values
AC voltage *V*	220
Frequency, *Hz*	50
The voltage at the output of the high voltage source (IVN), *kW*	20 ± 5

End of table 3.2.6

Effective air ionization volume not less than m^3	50
Continuous operation time, no more *h*	8
Ionizer power consumption from the network no more *W*	30
Dimensions, *mm*	364x281x66
Weight, *kg*	2

3.2.7 Gas analyzer DAG-500

A gas analyzer is a device designed to control emissions of harmful substances and optimize the operation of fuel installations by monitoring the content of the following components in the exhaust gas: oxygen, carbon monoxide, nitric oxide, sulfur dioxide, nitrogen dioxide.

The DAG-500 gas analyzer is a high-end multifunctional measuring instrument, the wide possibilities of which can be most fully manifested under the condition of competent instrument maintenance. It can be used for technical monitoring and use in various fields, including chemistry, the development of various technologies, the creation of fuel plants and engines. The device provides optimization of technological processes, thereby reducing fuel consumption and emissions of harmful substances.

The DAG-500 gas analyzer is a complete portable multifunctional device with means for sampling, data processing and recording the result on thermal paper and electronic information carriers. The instrument kit includes:

- the actual gas analyzer, which includes all the main components of the measurement, processing and registration;

- a probe with a thermocouple, a compensation wire, a gas hose, a condensate trap with an integrated filter for cleaning the measured gas;

- a power supply unit that ensures the operation of the device and charging the internal battery from the network;

- a case intended for laying the gas analyzer kit inoperative.

The appearance of the gas analyzer is shown in Picture 3.2.7.

Picture 3.2.7 - Appearance of the DAG-500 gas analyzer

Technical characteristics of this gas analyzer are presented in table 3.2.7.

Table 3.2.7 - Technical characteristics of the gas analyzer DAG-500

Parameter Name	Values
Memory	internal non-volatile, capacity of 200 records
Interface	RS-232
Calibration	200 seconds at O2-20.9%
	CO-SO2-NO-NO2 = 0 ppm in fresh air
Power supply	network - 220 V /50 Hz via remote source 12 V - 500 mA
	autonomous - from the built-in battery 6 V , 1.2 Ah
Battery Charge Time	no more than 14 hours, with protection against recharge
Battery life	at least 5 hours (without backlight), with discharge control

End of table 3.2.7

Operating temperature $°C$	+10 ... + 40
Storage temperature $°C$	-20 ... + 50
Gas intake probe	probe length 300..1500 mm with heat insulating handle
	type K (XA) built-in thermocouple and support cone
Device dimensions mm	220x110x70
Instrument weight kg	1.3
Case sizes mm	390x150x150
The total mass of the kit, kg	5,0

3.2.8 Industrial dryer

An industrial dryer is a tool with many names, probably for the reason that it is one of the most common and widely used tools in everyday life and in production.

Its structure is simple: an industrial dryer consists of a spiral heating an air, a fan supplying air heated by a spiral, and an electric motor with which the fan works. An industrial dryer is distinguished from an ordinary dryer by which hair is dried, with a power of 930-2300 W, temperature and amount of air blown out. Typically, industrial dryers have the same characteristics: delivers heated to a temperature of 500-600 $°C$ air, and blows - from three hundred to five hundred liters per minute.

The appearance of the industrial dryer is shown in Picture 3.2.8.

Picture 3.2.8 - Appearance of the industrial dryer Interskol FE-2000E

Technical characteristics of the Interskol FE-2000E industrial dryer are presented in table 3.2.8.

Table 3.2.8 - Technical characteristics of the industrial dryer Interskol FE-2000E

Parameter Name	Values
Power, W	2000
Air consumption, l / min	300-500
LCD display	not
Working temperature, $°C$	80-600
Temperature adjustment	smooth
overheat protection	Yes
Dimensions mm	260x80x200
Weight, kg	0.8

4 Experimental studies

4.1 Test sequence and experimental design

Any research begins with goal setting. The choice of a problem for study and its formulation affects both the research model and the conclusions that will be drawn from its results.

After choosing the goal of work, it should be determined the dependent variables. These are the variables that will be measured during the study.

Since there are dependent variables, there must also be independent variables. They are called factors. The researcher operates the factors in the experiment. The relationship between the factor and the dependent variable is conveniently represented using a cybernetic system, often called the “black box”.

A black box is a system whose operating mechanism is unknown to us. However, the researcher has information about what happens at the inlet and outlet of the black box. In this case, the state of the output functionally depends on the state of the input.

The combination of all possible states determines the complexity of the black box. So, a system of ten factors at four levels can be in more than a million different states. Obviously, in such cases it is impossible to conduct a study that includes all possible experiments. Therefore, at the planning stage, the question is solved about how many experiments and which ones are necessary to carry out to solve the problem.

In practice, there are no fully managed objects. Both managed and uncontrolled factors act on a real object, which leads to variability of the results between individual objects. We can only separate random changes from natural ones caused by various levels of independent variables using statistical methods.

The next step in planning experiments is randomization. Randomization is a process used to group objects in such a way that each of them has an equal chance of falling into a control or experimental group. In other words, the choice of research parameters should occur randomly, so that the study is not rejected in the direction of the "preferred" result for the researcher.

Randomization helps prevent biases due to causes that were not directly accounted for in the experiment. The randomization process is easy to implement using specialized statistical software or tables [36].

4.1.1 Progress of the experiment

The beginning of the experiment begins with a visual inspection of all the nodes of the experimental setup. After that, the gas supply opens on the cylinder, which is regulated by a reducer with a pressure gauge. Gas passing through the meter enters the burner. The valve for supplying gas to the nozzles opens and ignition is carried out through the pilot burner. Thus, the burner enters the operating mode. After that, the digital thermometer is turned on, and the temperature from the probes is displayed. Next, an air ionizer and a gas analyzer are turned on. The last one turns on an industrial dryer, on which the temperature of the blown air is set.

To conduct an experiment, it is necessary to adjust the parameters. During each experiment, several of them were regulated at once.

The first is a gas supply. It was controlled by opening and closing the adjusting knob, which reduced the flow area, thereby reducing the gas supply, which was monitored by the gas flow meter.

The second is the voltage applied to the ionizer. It is controlled by the output voltage stage selector. Due to this, a high voltage generator is affected and the number of ions in the air decreases in direct proportion to the output voltage.

The third is the temperature of the air supplied to the ionizer. It is regulated by lowering the temperature on an industrial hairdryer or by removing it to a greater distance. To more accurately determine the temperature that enters the input to the ionizer, a temperature sensor is installed for more precise adjustment.

Fourth is the coefficient of excess air. It is regulated thanks to the gas analyzer. The probes are mounted above the chimney in such a way as to capture the concentration of carbon monoxide in the exhaust products of combustion. Thanks to these readings, the gas analyzer calculates the coefficient of excess air. If the concentration of carbon monoxide begins to increase, then this is a sign that less air cannot be supplied. The air supply itself is limited by a gate, which prevents direct air from entering the burner.

After conducting all experiments, the results are recorded in the table, and the installation is turned off in the reverse order.

4.2 Planning an experiment

It is necessary to study the influence of the parameters of the flame ionization process on its combustion. Excessive load of the burner device, supplied voltage must be within certain limits, deviation from which leads to an increase in the coefficient of excess air and, as a consequence, a decrease in the efficiency of the installation as a whole. Based on the results of tests of previous years, it was found that the value of the coefficient of excess air most fully determines the combustion process, and it has limitations on the lower limit at which the efficiency decreases due to an increase in the content of carbon monoxide in the combustion products [37], [38], [39]. Therefore, the coefficient of excess air is selected as an effective sign. Variable factors adopted [41], [42], [43], [44]: burner load factor K_3 voltage supplied by the transformer at the output U ambient temperature $T_{ов}$. The selection of factor equations and their coding are given in table 4.1.1.

Table 4.1.1 - Selection of factor equations, factor coding

Level of Variable Factors	Code designation	$K_3,\ \%$	$U,\ kv$	$T_{ов},°C$
		X_1	X_2	X_3
Lower level	-1	30	20	20
Upper level	+1	100	45	150
Main level	0	65	32,5	85
Range of variation	$\vartriangle x_i$	35	12,5	65

To assess the influence of these factors and the mathematical description of the process, we use a first-order model [40]:

$$y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3 + b_{123}X_1X_2X_3. \qquad (56)$$

A full factorial experiment (PFE) is an experiment in which all possible, non-repeating combinations of factor levels are realized.

The number of experiments in PFE is determined in accordance with table 2. Usually there are plans for an experiment of the type 2^k (two levels of variation of factors), less often 3^k and very rarely with $p > n$ due to the sharp increase in the number of independent experiments (table 4.1.2).

Table 4.1.2 - the Number of experiments $N = p^k$

p \ k	2	3	4
2	4	8	16
3	9	27	81
4	16	64	256

Experimental conditions are usually written in the form of experiment planning matrices (table 4.1.3), where the rows correspond to various independent experiments and the columns correspond to the values (levels) of factors.

Table 4.1.3 - Experiment Planning Matrix 2^3

Experience Number	X_0	X_1	X_2	X_3	y
1	+	-	-	-	y_1
2	+	+	-	-	y_2
3	+	-	+	-	y_3
4	+	+	+	-	y_4
five	+	-	-	+	y_5
6	+	+	-	+	y_6
7	+	-	+	+	y_7
8	+	+	+	+	y_8

In PFE there are various levels of interaction of factors. Table 4.1.4 shows such interactions.

Table 4.1.4 - Planning matrix PFE 2^3 taking into account the interaction of factors

Experience Number	X_0	X_1	X_2	X_3	X_1X_2	X_1X_3	X_2X_3	$X_1X_2X_3$	y
1	+	-	-	-	+	+	+	-	y_1
2	+	+	-	-	-	-	+	+	y_2
3	+	-	+	-	-	+	-	+	y_3
4	+	+	+	-	+	-	-	-	y_4
five	+	-	-	+	+	-	-	+	y_5
6	+	+	-	+	-	+	-	-	y_6
7	+	-	+	+	-	-	+	-	y_7
8	+	+	+	+	+	+	+	+	y_8

Generally, plans like 2^k geometrically represent a collection of points located at the vertices of a hypercube located in a multidimensional space. The space enclosed within the hypercube is the area of experimental design.

PFE Planning Matrix 2^3 taking into account the interaction of factors is presented in table 4.1.4. To determine the coefficient of excess air during the ionization of air supplied to a gas burner of atmospheric type, it is planned to conduct three parallel experiments in each row of the PFE matrix, a total of 24. The experiments are randomized using a random number table. For example, starting from the second column of the table, we write numbers from 1 to 24, discarding more than 24 and repeating, then the table of the experiments has the form (table 4.1.5).

Table 4.1.5 - the order of the experiments

Planning Matrix Experience Number	1	2	3	4	five	6	7	8
Random procedure for implementing experiments	24	19	4	9	5	21	7	8
	10	15	2	23	12	14	13	16
	22	20	1	3	17	6	11	18

It is necessary to carry out statistical processing of the initial data: determine the absolute and relative measurement errors, discard the errors and correctly record the measurement result.

Following the algorithm for processing the results, we determine the arithmetic mean value of the quantity $y_1, y_2 ... y_n$ for the whole experiment:

$$\bar{y} = \frac{y_1 + y_2 + ... + y_n}{N} = \frac{1}{N}\sum_{i=1}^{N} y_i \, , \tag{57}$$

$$\bar{y} = \frac{1,92 + 1,93 + 1,92}{3} = 1,923.$$

Where N - number of experiments.

Next, it is needed to find the mean square error of the result separately for N measurements (measurement method error):

$$^{N}S = \sqrt{\frac{\sum_{i=1}^{N}\left(\bar{y} - y_i\right)^2}{N-1}}, \qquad (58)$$

$$^{N}S = \sqrt{\frac{(1,923-1,92)^2 + (1,923-1,93)^2 + (1,923-1,92)^2}{2}} = 0,0058.$$

Find the standard deviation of the arithmetic mean (the error of the result of a series of measurements):

$$^{n}S_{\bar{y}} = \frac{^{n}S}{\sqrt{n}}, \qquad (59)$$

$$^{n}S_{\bar{y}} = \frac{0,0058}{\sqrt{3}} = 0,003.$$

Find confidence intervals Δy for $\bar{y}$ (absolute error of a series of measurements).

We set the confidence probability α (for most engineering experiments choose $\alpha = 0,95$)

Table value $t(\alpha;n)$ based on the number of measurements and a given confidence probability α will be equal to 2,360.

We calculate the value of the confidence interval Δx:

$$\Delta y = {}^{n}S_{\bar{y}}\, t(\alpha, n), \qquad (60)$$

$$\Delta y = 0,003 \cdot 2,360 = 0,0071.$$

As a result, we find relative error of the result of a series of measurements:

$$\delta_y = \frac{\Delta y}{\overline{y}}\ , \tag{61}$$

$$\delta_x = \frac{0,0071}{1,923} = 0,0037\,.$$

The value of the random error in the case of the number of experiments N less than 10 is allowed in the range of 15-20%. In our case, the percentage error was 3.7%, which satisfies the condition for a correct experiment.

The test results carried out in accordance with the planning matrix and the data in table 4.1.5 are presented in table 4.1.6.

Table 4.1.6 - Test results

Experience Number	Excess air ratio α					S_i^2	$\left(\overline{y_i} - y_i\right)^2$
	y_{i1}	y_{i2}	y_{i3}	$\overline{y_i}$	y_i		
1	1,92	1,93	1,92	1,92	1,92	0,00003	$2,5\cdot10^{-5}$
2	1,41	1,40	1,39	1,40	1,41	0,00010	$2,5\cdot10^{-5}$
3	1,65	1,67	1,65	1,66	1,65	0,00013	$2,5\cdot10^{-5}$
4	1,35	1,34	1,33	1,34	1,35	0,00010	$2,5\cdot10^{-5}$
5	1,76	1,77	1,76	1,76	1,77	0,00003	$2,5\cdot10^{-5}$
6	1,32	1,30	1,31	1,31	1,31	0,00010	$2,5\cdot10^{-5}$
7	1,61	1,62	1,61	1,61	1,62	0,00030	$2,5\cdot10^{-5}$
8	1,28	1,27	1,25	1,27	1,26	0,00023	$2,5\cdot10^{-5}$

The dispersion of the entire experiment, that is, the measure of the scatter of the values of a random variable relative to its mathematical expectation, is defined as:

$$S^2(y)=\frac{1}{N}\sum_{i=1}^{N}S_i^2, \quad (62)$$

$$S^2(y)=\frac{0,00077}{8}=0,000096.$$

Where N - number of experiments;

$\sum_{i=1}^{N}S_i^2$ - the sum of the weighted average dispersion values, taking into account the number of degrees of freedom.

After calculating all the coefficients, equation (56) takes the form:

$$y=1,534-0,205X_1-0,065X_2-0,046X_3+0,039X_1X_2+$$
$$+0,005X_1X_3+0,017X_2X_3-0,013X_1X_2X_3. \quad (63)$$

Error in determining the coefficients:

$$S_b=\frac{S(y)}{\sqrt{Nr}}, \quad (64)$$

$$S_b=\frac{0,009789}{\sqrt{8\cdot 3}}=0,001998.$$

Where $S(y)$ - error of the whole experiment;

r - the number of parallel experiments.

To identify the significance of the coefficients of the regression equation, we construct a confidence interval with a width of:

$$2\Delta b = t_T \cdot S_b, \tag{65}$$

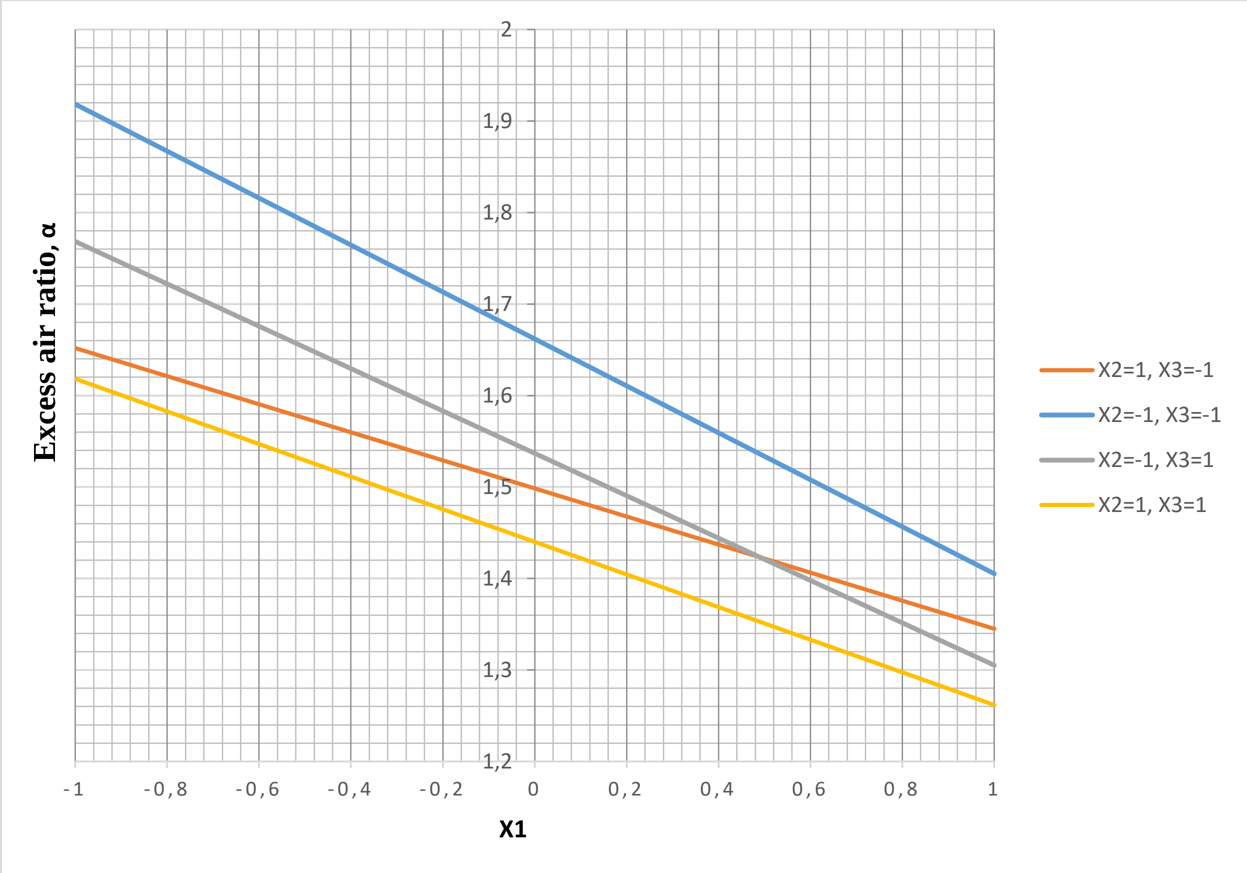
$$2\Delta b = 1,746 \cdot 0,001998 = 0,00698.$$

Based on the value of the confidence interval, the tabular value of t-student test $\alpha = 0,05$ and the number of degrees of freedom $d.f = 16$, it turned out that the coefficient b_{13} turned out to be statistically insignificant, therefore, the regression equation is rewritten and has a new form:

$$\begin{aligned} y = 1,534 - 0,205X_1 - 0,065X_2 - 0,046X_3 + 0,039X_1X_2 + \\ +0,017X_2X_3 - 0,013X_1X_2X_3. \end{aligned} \tag{66}$$

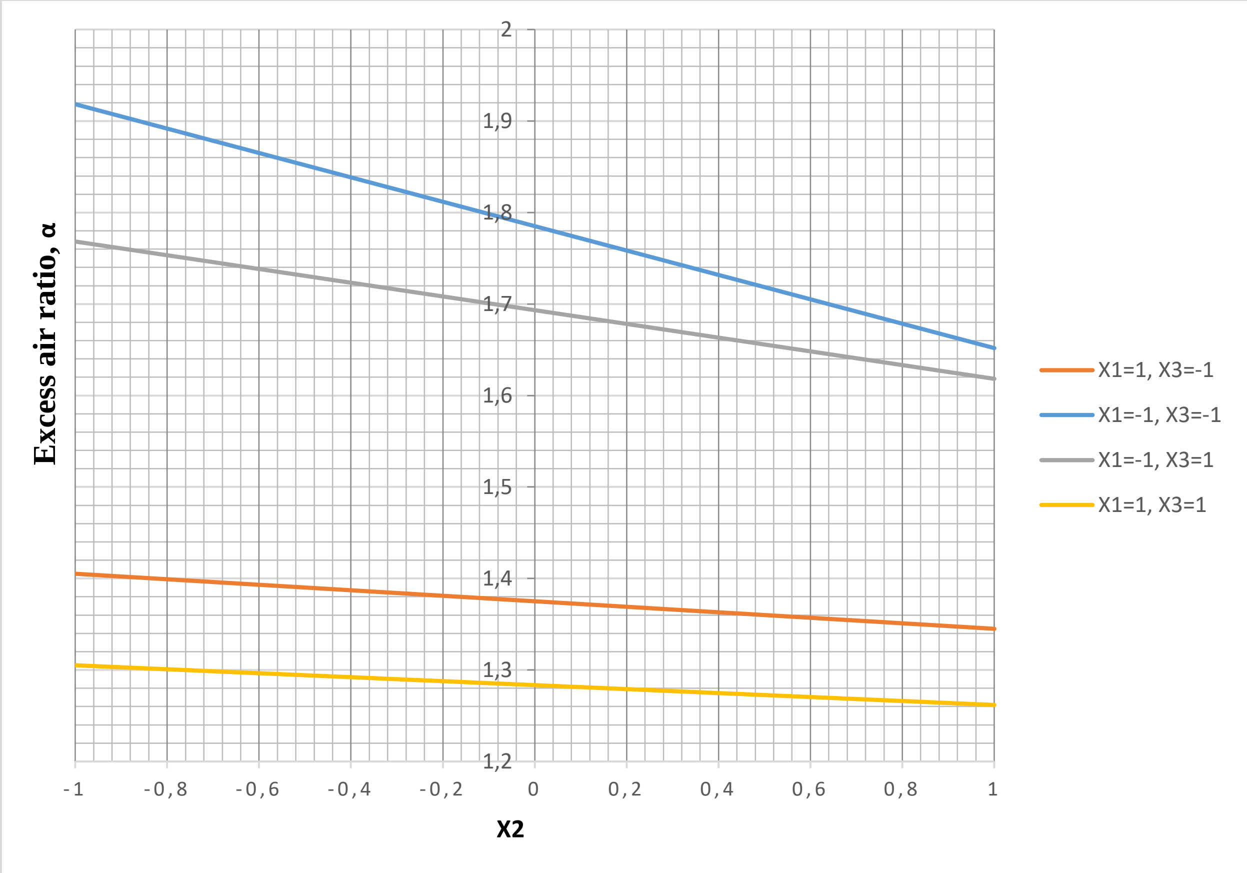
Estimated Values y_i are given in table 4.1.6.

A graph of the coefficient of excess air when changing the load factor of the burner K_3 (chart 4.1.1):



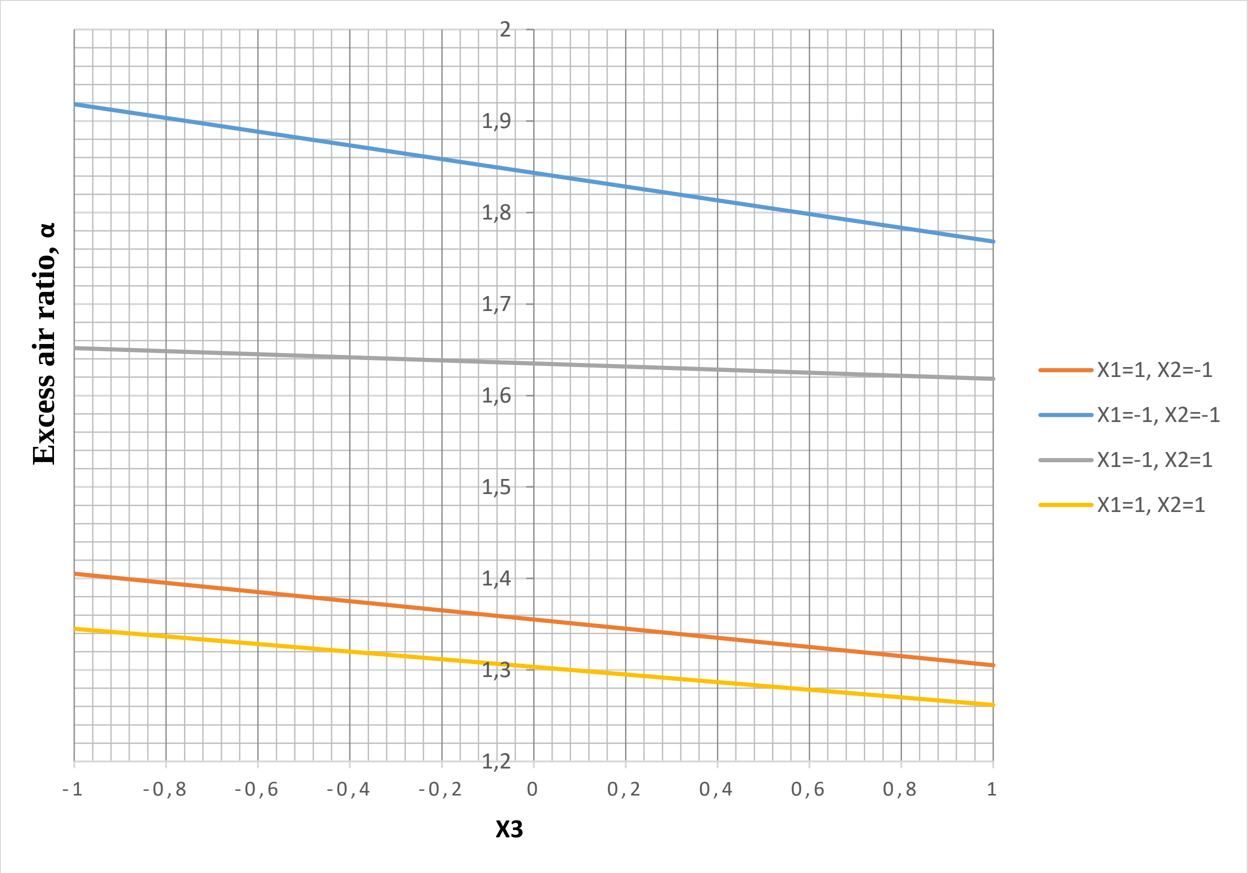
Picture 4.1.1 - Dependence α burner load factor K_3

The dependence of the coefficient of excess air when changing the voltage supplied by the transformer at the output U (chart 4.1.2):



Picture 4.1.2 - Dependence α from voltage U output transformer

The graph of the coefficient of excess air from changes in ambient temperature $T_{ов}$ (chart 4.1.3):



Picture 4.1.3 - Dependence α from ambient temperature $T_{ов}$

With an increase in all factors in the accepted range, a decrease in the coefficient of excess air in the range from 1,92 to 1,26 is observed. With fixed factors $X_1 = -1$ $X_2 = 1$, Y varies from 1,652 to 1,618. With fixed factors $X_1 = 1$ $X_2 = -1$, Y varies from 1.405 to 1.305. With fixed factors $X_1 = 1$ $X_2 = 1$, Y varies from 1,345 to 1,262, which is the best result.

The greatest influence of ionization has on the coefficient of excess air while reducing the load of the burner device, according to graph 4.1.1. Based on the experimental data, it can be concluded that ionization has a greater effect on the coefficient of excess air than an increase in the temperature supplied to the burner.

CONCLUSION

Comparative analysis of literature sources, past experience in air ionization, and means of influence on the combustion process of electric charge found that the use of ionized air as an oxidizer was proven to have a positive effect.

Analysis of literature sources has shown that the most acceptable way to ionize air for combustion is to influence the air with an electromagnetic field.

As a result of theoretical research, a database was formed, which later made it possible to narrow the number of experiments and focus on the most significant parameters.

Based on the gotten energy chains it was found that amplitude-frequency response characteristic graph has a distinct minimum that corresponds to the frequency of 7 radian per second, and the phase-frequency characteristic graph has two distinct inflection points of a function: a maximum and a minimum in the frequency range from 6 to 7 radian per second.

An elementary scheme of the experimental installation was compiled, on the basis of which it was assembled. This installation allows to perform experiments to determine the effect of air ionization on the combustion process.

A complete factorial experiment of the influence of the ionization process on the excess air coefficient in an atmospheric type burner was performed. As a result, a regression equation was constructed for the dependence of the excess air coefficient on the burner load, the temperature of the supplied air, and the voltage at the ionizer electrode, showing that all the factors significantly affect the excess air coefficient. With an increase in the value of factors in the experimental range, there is a decrease in the excess air coefficient by 34%.

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