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OPTIMIZATION OF NON-STATIONARY ELECTRIC FIELD PARAMETERS IN ORDER TO INCREASE THE EFFICIENCY OF CHAMBER FURNACES

Topicality. The presented work is devoted to the urgent task of increasing the energy efficiency of chamber furnaces. The purpose is to solve the problem connected with optimizing the parameters of the non-stationary mode of the applied electric field in order to increase the efficiency of the chamber furnaces. Methodology. According to well-known methods of experiment planning, we obtained a set of Pareto-incomparable solutions of the chamber furnace, taking into account the voltage between the burner and the metal charge, which is the basis of the algorithm. Findings. The work proposes an innovative system acting the process of metal heating in a chamber furnace. The result is a developed chamber furnace control system, in which the optimal values of control actions at each step of the heating cycle are determined according to the created algorithm. The proposed control system is universal, because after miscalculations it produces the dynamics, according to which one needs to change the value of direct-current voltage and gas supply with a step in time to perform any given mode of metal heat treatment. The experimental studies conducted on a real chamber furnace with a bogie hearth at Zaporozhye Titanium and Magnesium Combine confirmed this. The analysis of the obtained metal annealing temperature curve showed that the implementation of the optimal values of the control actions, obtained using the developed algorithm, provides a high uniformity and better quality heating of the metal. The dynamics of gas consumption by the chamber furnace during the heating cycle in the basic mode, without voltage supply, and under the condition of its use in accordance with the performed optimization testify to the possibility of significant energy efficiency improvement of the considered furnaces. Conclusions. For the first time we proved the possibility and efficiency of using a non-stationary electric field in the furnace chamber as a control action, which confirms the originality of the obtained results. The practical value of the research is that the developed control algorithm is universal in terms of metal heat treatment and can be used in chamber furnaces of any industrial enterprise, while one heating cycle reduces the consumption of natural gas by more than 10 %.
Key words: *electric field, experiment matrix, optimal control actions, optimization, set, functionals.*

А. А. ЄРОФЄЄВА, В. В. АРТЕМЧУК, Н. А. МУХІНА, О. П. КАРАСЬОВ
ОПТИМІЗАЦІЯ ПАРАМЕТРІВ НЕСТАЦІОНАРНОГО ЕЛЕКТРИЧНОГО ПОЛЯ З МЕТОЮ ПІДВИЩЕННЯ ЕФЕКТИВНОСТІ РОБОТИ КАМЕРНИХ ПЕЧЕЙ

Вперше доказано можливість і ефективність використання у якості керуючого впливу нестаціонарного електричного поля в камері печі, що підтверджує наукову новизну отриманих результатів. Практичне значення досліджень полягає у тому, що розроблений алгоритм управління є універсальним з точки зору режимів термічної обробки металу та може застосовуватись у камерних печах будь-якого промислового підприємства, при цьому за один цикл нагрівання зменшується споживання природного газу більш ніж на 10 %.
Ключові слова: *електричне поле, матриця експерименту, оптимальні керуючі впливи, оптимізація, множина, функціонали.*

А. А. ЕРОФЕЕВА, В. В. АРТЕМЧУК, Н. А. МУХИНА, А. П. КАРАСЕВ
ОПТИМИЗАЦИЯ ПАРАМЕТРОВ НЕСТАЦИОНАРНОГО ЭЛЕКТРИЧЕСКОГО ПОЛЯ С ЦЕЛЬЮ ПОВЫШЕНИЯ ЭФФЕКТИВНОСТИ РАБОТЫ КАМЕРНЫХ ПЕЧЕЙ

Впервые доказано возможность и эффективность использования в качестве управляющего воздействия нестационарного электрического поля в камере печи, подтверждает научную новизну полученных результатов. Практическое значение исследований заключается в том, что разработанный алгоритм управления является универсальным с точки зрения режимов термической обработки металла и может применяться в камерных печах любого промышленного предприятия, при этом за один цикл нагрева уменьшается потребление природного газа более чем на 10 %.
Ключевые слова: *электрическое поле, матрица эксперимента, оптимальные управляющие воздействия, оптимизация, множество, функционалы.*

Introduction

Currently, one of the priorities in Ukrainian industry is to increase production efficiency, due to the need to be competitive in the international arena. The issue of modernization is especially acute in metallurgical production. For many years, industrial enterprises have not actually undergone modernization, fixed assets are mostly obsolete, specific energy consumption is much higher (up to 7 times) than in the countries-producers of similar products. This situation leads to the fact that Ukraine has to sell either raw materials, which are extremely unprofitable in the strategic perspective, or low-quality and therefore low-cost products. That is, the existing problem can be divided into two parts: outdated equipment and technology and low energy efficiency of production processes. Of course, such problems need a comprehensive solution and indeed, much work is devoted to the modernization of metallurgical production [1–4].

However, as mentioned above, no less important is the problem of improving the energy efficiency of technological processes. This is based on the fact that metallurgy widely uses chamber heating furnaces that operate consuming natural gas. Such furnaces have become widespread due to the simplicity of design and operation, their versatility in terms of heating objects, the ability to regulate the temperature in the heating chamber. At the same time, they are not efficient in terms of flue gas recovery. Thus, according to

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[5] the heat losses associated with the emission of high-temperature flue gases into the atmosphere may exceed 50 % of the total heat capacity of the furnace. It is not possible to replace such furnaces with more modern ones and especially at all the enterprises simultaneously. Deep modernization of such furnaces requires large investments, but its economic feasibility is questionable. An important factor is that changing the position of the hoods and especially the burners may not always be effective in terms of the location of the charges, as the latter are not constant in size, and therefore the aerodynamics will change and heat fluxes will carry different heat energy to the object.

Another area of technology improvement in the metallurgical industry is the use of additional factors, such as heating of the incoming air mixture, the use of recuperators, and so on. In our opinion, one of the most promising areas is the use of electric fields. This assumption is confirmed by both foreign researchers and our own research. It should be noted that the use of electric fields requires little investment and has a convenient management system. Thus, the task of improving the chamber furnace efficiency through the use of electric fields is relevant.

When determining the initial parameters required for further research, it is necessary to take into account that the operation of chamber furnaces is periodic.

Purpose of the work

The purpose of this work is to solve the problem of optimizing the parameters of the non-stationary mode of the applied electric field in order to increase the efficiency of the chamber furnaces.

The object of research is the process of heating the metal in the chamber furnace.

The subject of the study is an energy-saving control system for the metal heating process in a chamber furnace.

Presentation of the main research material

Problem statement. According to the problem, we have a given temperature of the metal at a certain time, and τ is the time of its heating according to the temperature-time mode. The latter are regulated by technology in all phases of the heat treatment process in order to achieve the necessary thermo-physical transformations. Permissible temperature deviations are up to 50 °C and 20 °C for special conditions. Then the optimization task is to calculate the values of control actions to achieve the given dynamics of temperature changes with a minimum consumption of natural gas, for which it is necessary to develop appropriate parameters of the non-stationary electric field.

As control actions, it is proposed to use the voltage between the burner and the charge U in some range and the volume of gas supply at each step over

time. After calculating the optimal ratios of control actions according to the created algorithm, the control system must implement the sequence of changes in voltage and natural gas consumption to perform a given technological mode of heating.

Numerous scientific studies aimed to increase the energy efficiency of chamber furnaces relate to the definition and implementation in time of such temperature modes that provide the technologically necessary rate of metal heating.

The problem of using optimal energy-saving heating modes in chamber furnaces is considered in the work [6]. This paper proposes a heating mode in which the intensification of the process occurs at its final stage, which reduces the cost of thermal energy for maintaining a higher temperature of the workpiece. This approach allows to reduce not only the heat loss, but also the metal oxidation loss. However, in real production conditions, the recommended technological mode of heating is difficult to implement due to the problems associated with the need to take into account various design and technological constraints. In addition, to ensure energy-saving mode of metal processing, it is necessary not only to change the furnace hearth design, but also to be sure to have an operational forecast of the total hearth time of each workpiece.

In [7] it is proposed to change the position of the burners and draft hood openings, as well as to regulate the gas supply, trying to concentrate most of the thermal energy in the furnace chamber around the workpiece. From the point of view of problem statement and the control algorithm for gas supply in the furnace chamber developed by the author [7], the offered solution is interesting and logical. However, from the point of view of practical implementation it is quite difficult. Also, the proposed algorithm requires constant adjustments and refinements depending on the volumes and grades of steel billets, which complicates the process.

An interesting development is the technology by which gas is supplied to the furnace chamber in pulses [8]. This approach, according to the authors, has a number of advantages, namely gas savings, uniform heating of workpieces, increased productivity of the furnace. At the same time, there are significant disadvantages: there is no universal method for calculating the duration of fuel pulse, as well as its absence, which does not allow at the design stage to select the necessary burners and automatic control system for a particular unit; available burners installed on heating units, as a rule, cannot work under such modes and realize the specified heating. The literature [9] presents only some information on the practical implementation of such modes and cannot be considered universal.

As already mentioned, it is logical to try to use the heat of combustion products to heat the air and the

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fuel itself. Such devices can be heat exchangers of regenerative or recuperative type. But regenerative heat exchangers are actually impractical to use due to irrational fuel loss that occurs during the valve shift, which is peculiar for the use of regenerators. The use of recuperators would be more promising, but the problem is the variety of designs of industrial gas furnaces, which complicates the widespread use of recuperators. Besides, the efficiency of recuperators depends on the dimensions.

One of the options for using the heat of furnace gases is the use of regenerative burners, which according to the authors [10] can reduce fuel consumption by up to 30%. The main disadvantage of this method is the uneven heating of the metal with a hot flame, both on the metal surface and on the cross section of the heated products, which occurs due to increased heat flux on the metal surface from the flame side. At such combustion of fuel with high-temperature air one can also observe local overheating and even melting of metal with a hot flame in the furnaces [5]. So all these disadvantages are associated with too concentrated source of energy.

This work is a development of the research done by the author in previous works [11–14]. These works discuss the perspective direction of use of the additional influencing factor, namely an electric field. It has been proposed to use a stationary electric field, which is quite easy to use, but it is not always advisable to use an electric field throughout the heat treatment process of workpieces, and as our research shows, there are reserves for energy savings.

As for the mathematical apparatus, a lot of theoretical research is devoted to determining the optimal modes of operation of heating furnaces. In this work [15], authors numerically study the volumetric combustion and influences of small- and large-scale recirculation ratios of furnace gases, the influence of temperature fluctuation on the regenerator nozzle, and the working parameters at the starting phase and reverse. There is still a lot of theoretical research on solving optimization problems [16, 17]. However, it should be noted that most of them are devoted to the tasks of optimal combustion of gas mixtures or the structure of the furnaces themselves. Thus, a natural question arises about the search for rational algorithms for controlling the electric field as an additional influencing factor.

Theoretical part. As it is known, the flame contains charged particles in fairly large concentrations. This means that the electrophysical action can be carried out in two ways: by applying of electric, magnetic and combined fields to the flame or the introduction of charged particles from the outside to the latter. That is, various mechanisms of ion formation in the flame are possible and it is known that the mechanism of chemical ionization is responsible for the high concentration of ions in it. The main idea of using an electric field is

that in case of the formation of an electric field between, for example, a burner and a workpiece, the heat flux will be closer to the latter. This will be due to the fact that the electrified particles of combustion products will approach the specified surface and create an additional temperature zone near it, increasing the rate of its heating [11–13]. That is, the mechanism of possible influence of the electric field on the propagation of heat flux assumes that ions and electrons, acquiring sufficient energy of translational motion, in the process of inelastic collisions with each other and with the heating surface will create new active centers in the form of free atoms, radicals, new charged or excited particles. In other words, the electric field, acting on the ionized particles, can form a thermal barrier that allows to adjust the heat fluxes and thus affect the temperature of the workpiece. However, the complexity of this problem is the need to develop a rational algorithm for controlling the electric field in case of its non-stationarity. This follows from the conditions requiring to comply with the established technological parameters, in particular regarding the workpiece temperature in the chamber at a certain point in time. Previous studies have experimentally proven the savings in gas consumption by 11 % by applying an electric field [14]. Then it related to the use of a stationary electric field with an operating voltage of 1000 V and the operation of the unit throughout the operating cycle without cooling, i.e. heating and holding. The use of non-stationary modes involves the development of appropriate control algorithms, or voltage parameters, and so on.

We selected several variants in the set of the conducted theoretical research to compare and understand the general trends in solving the problems. The developed forms of pulses are given in Fig. 1. In the course of theoretical researches it was necessary to determine the optimal parameters of the presented pulses according to the criterion of minimum energy consumption while maintaining the temperature modes set by the technology and to compare them with the stationary mode.

As Fig. 1 shows, the pulse consists of two components:

$$t_i = t_{i_1} + t_{i_2}.$$

The initial pulse t_{i_1} aims to maximally affect the ionized charged particles of the gas mixture combustion products. That is, in the initial time, for example, for the first variant ($t_{i_1} = 1\,\text{s}$) the ionized particles, including the most distant ones, under the action of electric field force, are attracted to the object (workpiece). In other words, in the initial period t_{i_1} we can observe the attraction, concentration and retention of ionized particles.

Under the action of part of the pulse during the time t_{i_2} the ionized particles continue to be held near

the workpiece, some of them are lost, the part falls into the zone of electric field and is attracted to the object. That is, in fact, the main function of the second phase of the pulse is the retention of charged particles.

As for the pause t_p, it does not make physical sense, but is needed only in terms of saving electricity. When conducting the relevant research, one of the

tasks of optimization was to understand the allowable value of the pause time.

To solve this problem, let each possible variant be determined by the list of predictors $\Omega = [\omega_1, \omega_2, \ldots, \omega_n]$, selected at the stage of structural modeling, and each predictor ω_i can take some values $\Xi_i = \{\theta_{i1}, \theta_{i2}, \ldots, \theta_{ik}\}$, $i = 1, n$, indicating a possible mode of operation (Fig. 2).

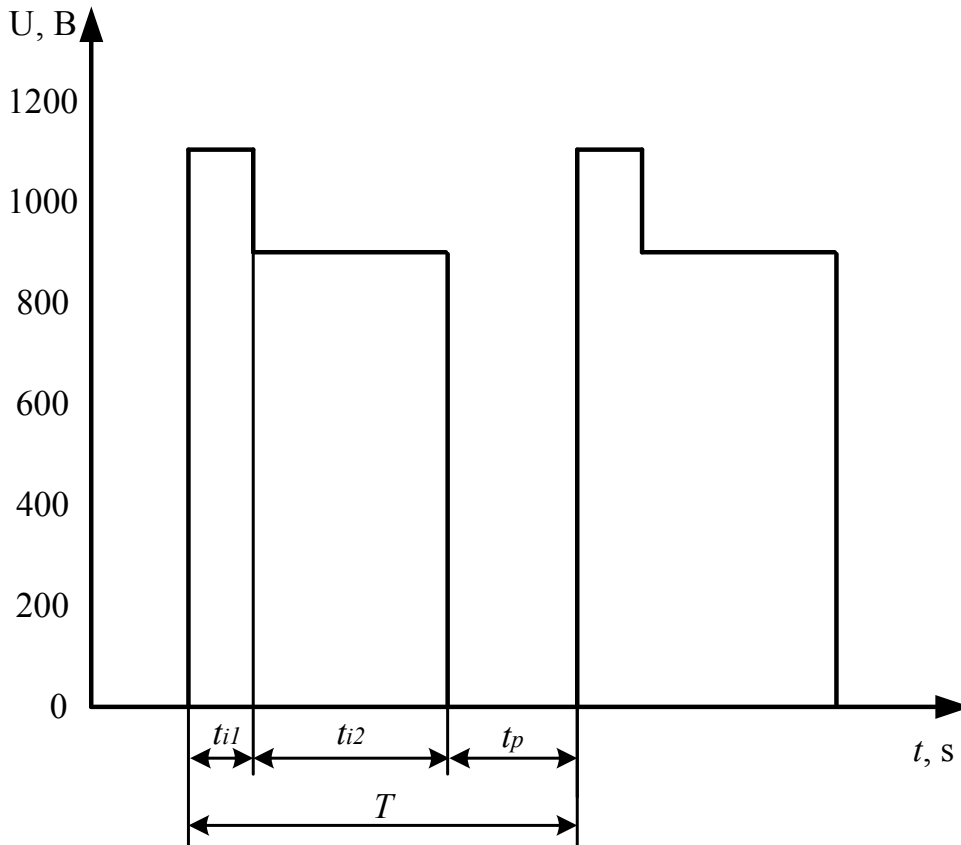Fig. 1 – Shape of pulses for creation of non-stationary electric field in the furnace chamber:
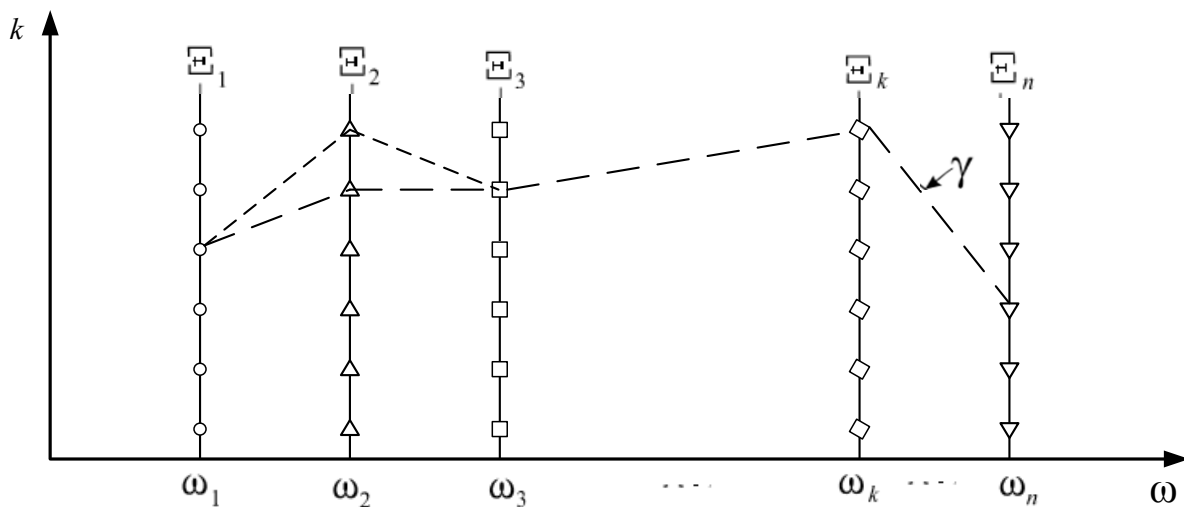t_{i_1} – initial pulse; t_{i_2} – main pulse; t_p – pause; T – period

Fig. 2 – Set of all possible selectors

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Definition. The list

$$\gamma = \left[\!\left[\omega_1, \theta_{1_{j_1}}\right], \left[\omega_2, \theta_{2_{j_2}}\right] \dots, \left[\omega_n, \theta_{nj_n}\right]\!\right]$$

will be called the selector γ.

The set of all possible selectors will be denoted as Γ set, in which the number of elements can be determined by the formula:

$$|\Gamma| = \prod_{i-1}^{n} k_i \ ,$$

where k_i – is the number of possible values θ_{ni} of ω_i predictor.

In the future, any selector $\gamma \in \Gamma$ will be characterized by two indicators: $F_1(\gamma)$, and $F_2(\gamma)$.

The desire to make the consumption of electricity and natural gas as little as possible, leads us to the problem of vector optimization, which has the form:

$$\begin{pmatrix} F_1(\gamma) \\ F_2(\gamma) \end{pmatrix} \to \min \ ,$$

where $F_1(\gamma)$, $F_2(\gamma)$ are the electricity and natural gas consumption values, respectively.

The solution of the vector optimization problem is a set $\Gamma_* \subseteq \Gamma$ in which any two selectors γ'_* and γ''_* are Pareto-incomparable in relation to each other.

Thus we will consider that two selectors γ_1 and γ_2 are Pareto-equal in relation to each other (we will symbolically write them down in the form $\gamma_1 P \gamma_2$), if

$$\gamma_1 P \gamma_2 \leftrightarrow \begin{pmatrix} F_1(\gamma_1, m) \le F_1(\gamma_2, m) \\ F_2(\gamma_1, m) \le F_2(\gamma_2, m) \end{pmatrix},$$

while one of the inequalities is performed strictly.

If the set of predictors Ω and the set of possible values $\Xi_i, i = \overline{1, n}$ are finite, then the solution of the problem exists.

We should note that by defining a set of rational selectors and having information about the state of the object under study, we get the opportunity to rationally influence the state of the object, going to the nearest selector for the optimal solution of the problem.

Among the many calculated variants for example, we give a fragment of the 10 possible and most acceptable variants (Table 1).

In this case, among the 10 possible variants presented (Table 1) for further study, we leave only three, because the total costs in any other modes of operation exceed the costs of variant 5 (stationary mode, the average voltage was 1000 V), with which we compare other variants. So, let us consider the first, fourth and eighth variants.

Table 1 – Parameters of non-stationary electric field mode in the furnace chamber

Var. No.	U_1, V	t_1, s	U_2, V	t_2, s	t_p, s	U_{av}, V	G, m³/cycle	Electricity consumption, kWh	Gas costs, UAH	Electricity costs, UAH	Total costs, UAH
1	1100	1	900	3	2	633.33	467.58	12.67	2520.24	37.24	2557.48
2	1200	1	900	3	2	650.00	473.22	13.00	2550.66	38.22	2588.88
3	1100	1	950	3	2	658.33	470.38	13.17	2535.36	38.71	2574.07
4	1200	1	800	3	2	600.00	469.72	12.00	2531.80	35.28	2567.08
5	1000	–	1000	–	0	1000.0	466.03	20.00	2511.74	58.80	2570.54
6	1000	1	900	3	2	616.67	487.30	12.33	2626.55	36.26	2662.81
7	1000	1	800	3	2	566.67	478.58	11.33	2579.53	33.32	2612.85
8	1200	0.5	800	3.5	2	566.67	469.84	11.33	2532.45	33.32	2565.77
9	1100	1	900	4	2	470.00	496.78	9.40	2677.65	27.64	2705.29
10	1000	1	900	3	2	616.67	474.51	12.33	2557.59	36.26	2593.85

As we can see, they are all Pareto-incomparable, so they are the solution of the vector optimization problem by two indicators. But since the first variant has the lowest total cost, it can be recommended for future use.

Experimental part. To conduct the necessary experimental studies aimed at assessment of the impact of the developed modes of the controlled non-stationary electric field on the distribution of heat fluxes in the heating chamber, we used a special designed furnace unit (Fig. 3).

The results of experiments using a non-stationary electric field were compared with the results obtained at steady state, i.e. when applying a constant electric field, whose device circuit diagram is shown in Fig. 4.

The working chamber of the furnace with internal dimensions of 0.192×0.192×1.1 m is lined with lightweight refractory bricks. Natural gas was used as a fuel, thanks to which a maximum heat output of 77 kW was achieved with the help of a standard burner. Natural gas and air consumption were measured with the Gallus 2000 G4 type gas meter *15* and the standard measuring diaphragm *16*, respectively. The electrical part of the experimental unit allows to change the operating direct voltage of a given polarity applied to the electrodes *5* and the burner *2*, in the range of 0…1100 V. To avoid measurement errors associated with the effect of applying voltage to the

thermocouple elements, we chose a non-contact method using laser pyrometers, which allowed to obtain reliable temperature values in the required places of the chamber. Remote access to the latter was carried out through special holes made of refractory glass. For all the experiments, the specific consumption of natural gas was 0.04 m^3/min.
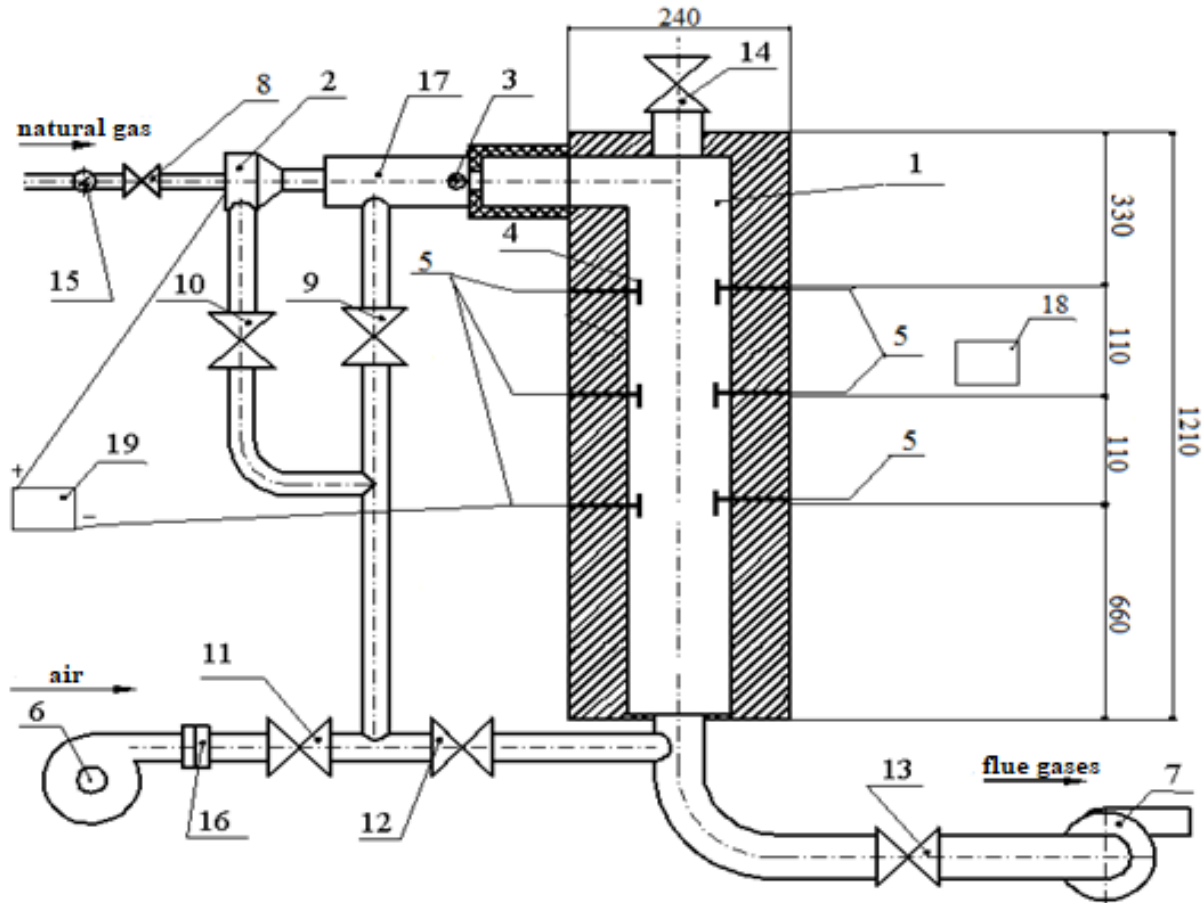
Fig. 3 – Schematic diagram of the experimental unit:
1 – heat-insulated furnace chamber; *2* – burner; *3* – electrospark igniter;
4 – moving plate under voltage; *5* – electrodes; *6* – blower; *7* – smoke exhauster;
8–14 – combustion process regulation fittings; *15* – gas meter; *16* – measuring diaphragm;
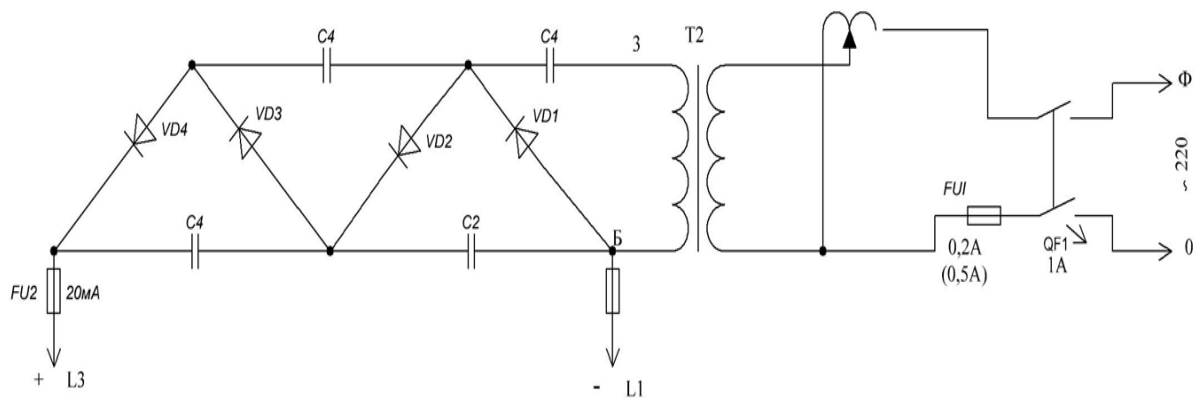*17* – auxiliary chamber; *18* – temperature measuring device, non-contact; *19* – voltage source

Fig. 4 – Diagram of electrical device for obtaining constant voltage with ability
to change its value in the range of 0…1100 V: *L3* – pole-plate; *L1* – burner

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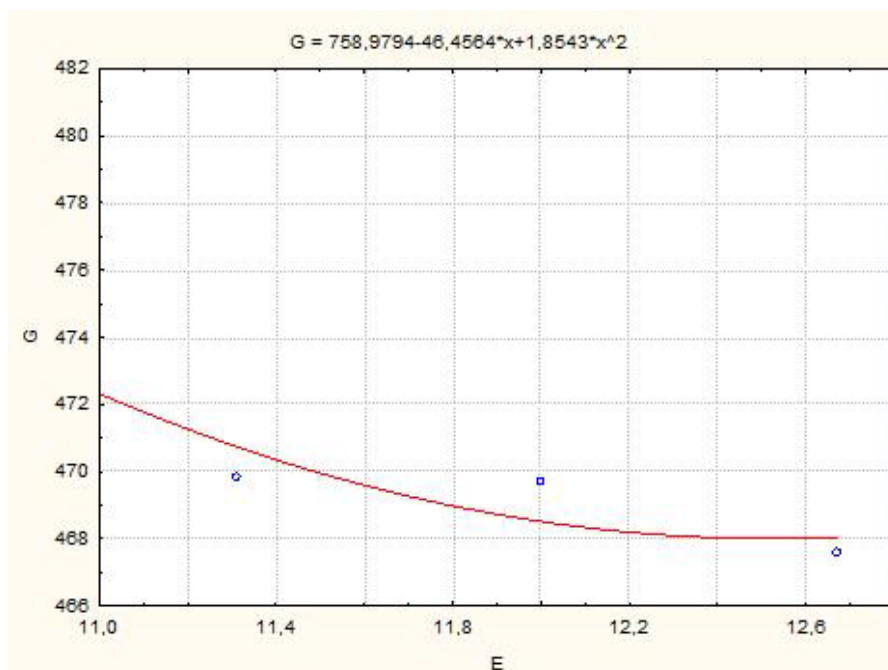та теплотехнічні процеси й устаткування, № 2(4)'2020*

Fig. 5 – Set of Pareto optimization problem solutions:
E – Electricity consumption (kWh); *G* – Natural gas consumption (cub. m);
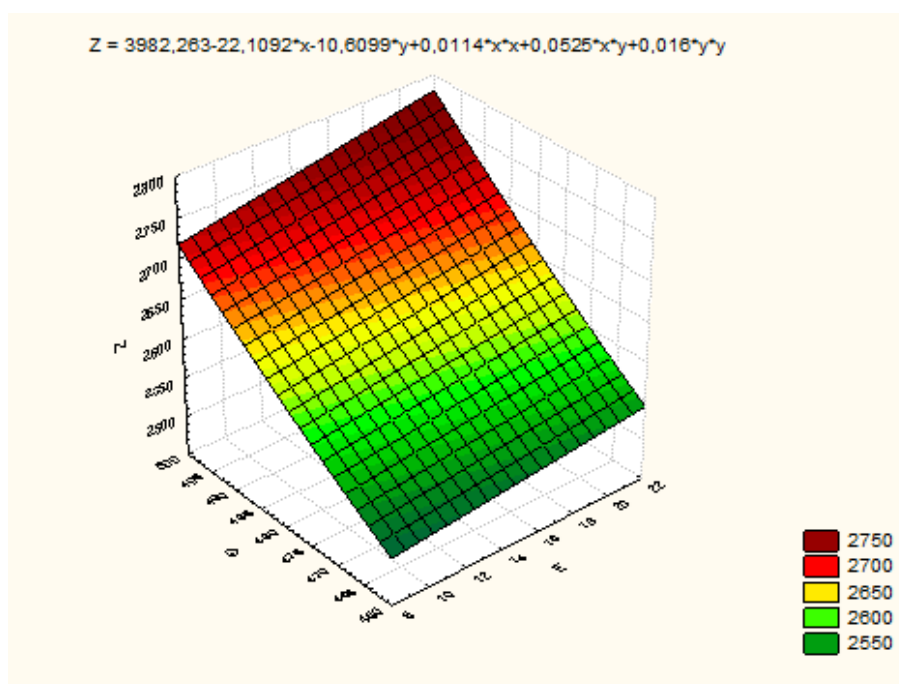dots – experiment; line – approximation

Fig. 6 – Set of Pareto optimization problem solutions (three-dimensional)
in view of the total cost of energy resources

Results and discussion

Based on the conducted theoretical and experimental researches we obtained the results determining the optimization of voltage impulse parameters according to which the resulting dependence of Pareto infinite solutions was constructed (Fig. 5, 6).

The analysis of the above results shows that the obtained dependences of the optimization problem solutions by the minimum energy consumption criterion are Pareto-incomparable. However, taking into account the total cost indicator among the presented variants, we would propose to adopt the first one (Table 1). Also in the course of the research it was found

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that increasing the pause for more than 2 seconds is impractical. It can be assumed that due to the high turbulence in the furnace chamber and the intense movement of heat fluxes, there is a decrease in the concentration of charged particles near the object, and as a result, gas consumption increases. Herewith, electricity savings are insignificant and do not actually affect the total savings. That is, it is appropriate to propose to set the maximum pause time for no more than 2 seconds, during which, due to the process inertia, most of the charged particles remain around the workpiece. After the pause, there is again a shock action on the ionized particles, the process is repeated. The maximum values of the pulses were selected for the same reasons, namely the most effective effect on the particles, approach and retention near the object.

Conclusions

On the basis of the conducted researches it is possible to draw a conclusion that application of a non-stationary electric field is expedient from the point of view of energy efficiency. According to the set task, we developed the workpiece heating mode with the use of non-stationary electric field, which allows to increase the energy efficiency of the process of heat treatment of objects. In comparison with the stationary mode, the proposed technology allows to save 33% of electricity at almost the same gas consumption, which is attributable to the peculiarities of thermophysical processes in the furnace chamber. Another advantageous feature of the developed technology is the possibility of a more rapid effect on the workpiece temperature (up to 8 %), which was discovered during the experiments and requires further research. The disadvantage of the proposed technology is the more complex electrical equipment. However, given the modern development of power electronics, this issue is not a problem.

The originality of the obtained results: for the first time we developed and substantiated the optimal control of a non-stationary electric field in the working chamber of the furnaces, which allows to increase their energy efficiency.

The practical value of this work is the ability to respond more quickly and influence the current temperature of the object.

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