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SIMULATION OF THE WORK OF GLASS FURNACES WITH THE PURPOSE OF SEARCHING FOR RESERVES AND INCREASE THEIR EFFICIENCY

The object of research is the operation of a glass furnace. The work involved modeling the operation of a glass furnace by changing the technical and economic indicators of its operation in order to optimize the technological processes of manufacturing glass products, increase the energy efficiency of the process, and reduce the ecological burden on the environment. Glass furnaces are complex heat engineering units that require a large amount of energy to operate. Therefore, increasing their effectiveness is the main task of our research. In the work, computer modeling of thermal processes in the furnace was carried out, heat balances were calculated and analyzed, and the performance of the furnace was analyzed after changing and improving the technological regimes of combustion processes, glass boiling and furnace construction. Studies have shown that in order to increase the technical and economic performance of glass furnaces, it is advisable to conduct additional thermal insulation of the furnace enclosures. The thermal insulation of the vault increases the efficiency of the furnace by 2–3 %, and the thermal insulation of the remaining areas of the furnace in total allows to increase the efficiency of the heating unit up to 3 %. Such measures improve the sanitary and technical working conditions of the staff in the machine-bath shop. Studies have shown that additional heating of the air used for burning fuel significantly increases the efficiency of the furnace. Thus, an increase in air temperature by 100 °C increases the efficiency of the furnace by approximately 2.5 %. However, such a measure is possible with a corresponding increase in the volume of regenerator nozzles. A significant increase in the efficiency of the furnace was achieved when additional electric heating was installed. This allows to reduce the total energy costs, and at the same time, the introduction of every 10 % of additional electric heating increases the efficiency of the furnace by up to 3 % and improves the quality of the glass mass. Such additional heating can be recommended in the amount of 20–30 % of the total heat consumption for the operation of the furnace. The analysis of the obtained results showed a fairly good convergence of the results, which indicates the acceptable adequacy of the models. The obtained process simulation results allow choosing the optimal design and operation parameters of the glass furnace. The results of the work can be used in practice for the design of efficient glass furnaces of various purposes and performance.

Keywords: *glass furnace, regenerators, combustion, electric heating, computer simulation of technological processes.*

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1. Introduction

Glass boiling is a high-temperature process that requires a significant amount of energy. Thus, the boiling of industrial silicate glass takes place at a temperature of about 1500 °C. Traditionally, the energy used to operate the glass furnace was provided mainly by fossil fuels [1]. At the same time, more than 75 % of the total energy required for the production of glass products is consumed by the melting furnace. Therefore, increasing the efficiency of glass furnaces is the subject of constant research on improving the technological modes of its operation [2]. Due to the urgent need to reduce greenhouse gas emissions, the main attention of design engineers is directed to the further optimization of glass melting processes. In fact, the only way to reduce CO_2 emissions is to reduce energy consumption [3]. The difficult situation with energy resources forces us to fundamentally change the policy of energy consumption in industry, including at enterprises of the glass industry. The experience of foreign countries shows that the creation of a highly efficient and competitive industrial sector is possible only by reducing energy costs per unit of production [4].

In recent decades, various concepts have been proposed to intensify industrial high-temperature processes and help directly reduce the specific energy demand of the furnace. For example, the use of regenerators that allow the use of flue gas energy [5]. In regenerators, the air for combustion is preheated by spent flue gases, which makes it possible to reduce the use of fossil fuels and achieve higher process temperatures. To increase the air temperature, it is advisable to increase the size of the regenerator. This approach can be combined with pre-heating of the charge and broken glass, which allows to significantly reduce the specific energy consumption of the furnace [6].

Also, to increase the efficiency of furnaces, fuel combustion in air with an increased content of oxygen or pure oxygen fuel is used [3, 7]. By increasing the volume fraction of oxygen in the air from 21 vol % to 100 vol %, higher flame temperatures can be achieved. In addition, the reduced nitrogen content in the flue gases leads to enhanced radiation heat exchange and increases the overall energy efficiency [8]. According to this technology, it is possible to use the spent heat of oxy-fuel furnaces in thermochemical recovery (TCR), where flue gas recirculation is combined with regeneration and reforming stages. This leads to the formation of synthesis gas ($CO+H_2$), which can be re-burned [9, 10]. However, the technology still requires serious research before it can be implemented on an industrial scale.

Currently, the most effective way to increase the performance of a glass furnace is to use heating electrodes for additional electric heating of the glass furnace. In [11], it was proved that the local supply of electrical energy or gas pulse significantly affects the flows and temperature field in the glass melt. Such approaches allow to improve the quality of glass and intensify the work of the furnace. This overview was obtained by performing batch numerical simulation studies of an industrial-scale glass furnace in Fluent 19.0. A novel aspect of this work is that the results are direct, allowing the demonstration of differences between these conventional physical cleaning techniques [12].

In recent years, the use of numerical methods is gaining popularity for the optimization of high-temperature processes in order to increase energy efficiency and improve product quality. By performing CFD (Computational Fluid Dynamics) modeling, it is possible to study in detail the effect of changing the parameters of the condition and analyze the results. The first models took into account the change of conditions in a very simplified way [13] and did not provide an opportunity to evaluate the processes as a whole. More sophisticated CFD eventually offered models combining the relationship between the separately calculated combustion space and the glass boiling bath [14]. In [15–17], three-dimensional models of an air-fuel regenerative furnace were developed and compared using the basic vortex scattering approach, which does not allow for multi-stage chemistry. The base case without additional energy efficiency measures was compared with the case for which additional electric furnace heating was applied. Studies have confirmed increased furnace productivity and improved glass quality. In general, this study considered the non-trivial problem of combining several physical effects in order to optimize the efficiency of the melting process. The complex nature of these works made it possible to describe the mechanisms of heat transfer occurring in an industrial furnace, and especially regarding the role of the melt flow.

The scientific aim of this research is the development of the computer program OptimaGlassfurnace, which is based on classical engineering heat engineering calculations. The program provides for the input of variable values of the parameters of the heat engineering unit and allows to obtain data on the operation of the furnace, which allows to optimize its operation.

Unlike other studies described in the literature, the developed model allows to change the parameters of the furnace in a wide range, allows to enter a large number of variable parameters, is based on the methodology of engineering calculations, and has exceptionally high accuracy.

The practical part of the aim allows to take into account the possibilities of carrying out energy-saving measures in production and divided them into two groups. The first includes measures that do not change the fundamental basis of technology and production techniques. They are designed for 1–2 years and do not require capital-intensive solutions. In the conditions of inefficient use of energy resources, which is characterized by the glass industry, it is possible to reduce fuel and electricity costs by 10–15 % within a short period of time and without significant capital investments. The second group of measures includes the creation of technological units and systems of a new generation, distinguished by extremely high energy-saving and ecological characteristics. As large consumers of heat, the existing glass furnaces have a relatively low thermal efficiency, which does not exceed 30–40 %. In this regard, the issue of intensifying the work of existing furnaces and saving fuel is an urgent task. Due to the fact that the fleet of furnaces is extremely diverse in terms of design, sizes and technological purposes, in combination with the complex scheme of heat and mass exchange processes occurring in the furnaces, there is no reliable single method for calculating glass furnaces. The existing methods do not provide comprehensive answers for operators regarding the choice of the optimal operating mode of the furnace unit. And here, research works that allow to reveal the influence of individual factors on the operation of the furnace in general are of great importance.

2. Materials and Methods

To simulate the operation of a glass furnace in the OptimaGlassfurnace program, it is possible to change the following parameters:

– *furnace performance*;

– *energy resources* (type of fuel, calorific value, power of additional electric heating);

– *charge* (charge consumption per 1 kg of glass mass, yield of degassing products of the charge, chemical composition of degassing products, humidity of the charge);

– *glass mass* (theoretical heat consumption for boiling 1 kg of glass mass, which consists of heat consumption for the processes of silicate and glass formation, physical heat of the conditioned glass mass at the maximum boiling temperature, heat of heating the products of degassing; glass melting heat, and also taking into account the heat capacity of the glass mass, the maximum boiling temperature, temperature at the bottom of the pool, temperature of production of flow coefficient (Novak number));
– *combustion process* (temperature of flue gases (flame temperature), degree of blackness of the flame, temperature of spent flue gases, temperature of air entering combustion, air consumption per 1 m^3 (n. c.) of natural gas, output of flue gases per 1 m^3 (n. c.) of natural gas and the chemical composition of combustion products);
– *overall dimensions of the furnace* (dimensions of the furnace basin, dimensions of the flame space, dimensions and number of inlets of burners and loading pockets);
– *laying of the main fences of the furnaces* (separate data on four characteristic areas of the furnace: vault, walls of the flame space, walls of the pool, bottom of the pool. Type of refractory and heat-insulating layer, their thickness, coefficient of thermal conductivity).

The OptimaGlassfurnace program allows to identify items of unproductive heat energy consumption and outline ways to minimize them. In addition, it allows to vary any initial parameter and at the same time analyze the change in the resulting characteristic. This makes it possible to carry out theoretical research on obtaining generalized data on the influence of one or another factor on the technical and economic characteristics of the furnace, as well as to solve optimization tasks.

Two variants of furnaces with a capacity of 100 t/day were chosen for simulation. The first option with a specific removal of glass mass of 1000 kg/(m^2·day) (a furnace with a transverse flame direction is adopted), the second with a specific removal of glass mass of 2000 kg/(m^2·day) (a furnace with a horseshoe-shaped flame direction is adopted). Also, for these options, additional parameters were introduced – two masonry options (the first – a furnace without additional insulation, the second – a furnace with additional high-efficiency thermal insulation). It is also possible to take into account the thickness of effective thermal insulation for individual elements of the furnace enclosure; the temperature of the heated air; share of heat, which is introduced at the expense of electricity. Processes were simulated according to the set parameters and the following information was obtained:
– gas consumption;
– furnace efficiency;
– profitable articles of the heat balance in absolute values and in percentage terms;
– expenditure items of the heat balance in absolute values and in percentage terms;
– values of heat losses through individual sections of the glass furnace enclosure (in absolute values and in percentage terms);
– temperature distribution in the lining of the furnace fences (in a multi-layer wall).

Research results are displayed in the form of numerical values and diagrams.

3. Results and Discussion

As a result of modeling the processes of furnaces with a capacity of 100 t/day: the first with a specific removal of 1000 kg/(m^2·day) for a furnace with transverse flame development and the second with a specific removal of 2000 kg/(m^2·day) for a furnace with a horseshoe direction flame. It is possible to introduce additional parameters and made calculations for two masonry options: the first – a furnace without additional insulation, the second – a furnace with additional high-efficiency thermal insulation. The obtained results are shown in Fig. 1.

Studies have confirmed that the most significant item of energy loss is heat carried away by flue gases. It is about 60 %. These losses cannot be called irrecoverable losses. Part of this heat is returned with the air coming from the regenerates for combustion.

In second place in the cost items are costs for the glass formation process. They make up 21 % and refer to productive costs. In third place are heat losses due to the furnace enclosure. Their share varies from 5 % to 11 %. The first value refers to a furnace with a large specific removal without thermal insulation, the second to a furnace with a small specific removal and thermal insulation. Intermediate values occur in furnaces with a large specific removal, but without thermal insulation – 8 %, and with a small specific removal, but with thermal insulation – 7 %.

Thus, increasing the specific removal of glass mass by two times (and at the same time reducing the main dimensions of the furnace), in terms of reducing losses through the walls of the furnace, is similar to the use of effective thermal insulation of the original low-performance furnace.

In the fourth place – losses due to furnace openings. They amounted to 6–7 % for a large low-performance furnace and 3–4 % for a small high-performance furnace.

In the last place are losses with reverse convection flow. This value is up to 4 %.

Thus, the optimization of technical and economic indicators of furnaces can be carried out in three directions:

1. Reduction of non-productive costs due to the furnace enclosure can be achieved by improving the thermal insulation of the furnace, and primarily the vault.

2. Reduction of unproductive expenses with the heat of outgoing gases by increasing the degree of regeneration of this heat. Such an effect can be obtained by increasing the volume of the regenerator, which will increase the temperature of the air entering the combustion.

3. Reduction of non-productive costs with the heat of outgoing flue gases is possible by introducing additional electric heating of the furnace.

The study of the effectiveness of thermal insulation of various areas of the furnace showed that it is most appropriate to perform thermal insulation of the vault. At the same time, it is possible to use backfills that have very low values of thermal conductivity, for example, diatomite. When insulating the vault, gas consumption per 1 kg of glass mass can be reduced by 11 % (in a furnace with a low specific removal) and by 7 % (in a furnace with a high specific removal). At the same time, the efficiency will increase by 13 % and 8 %, respectively. It is important to emphasize that the desired result can be achieved with an insulation thickness of about 10 cm.

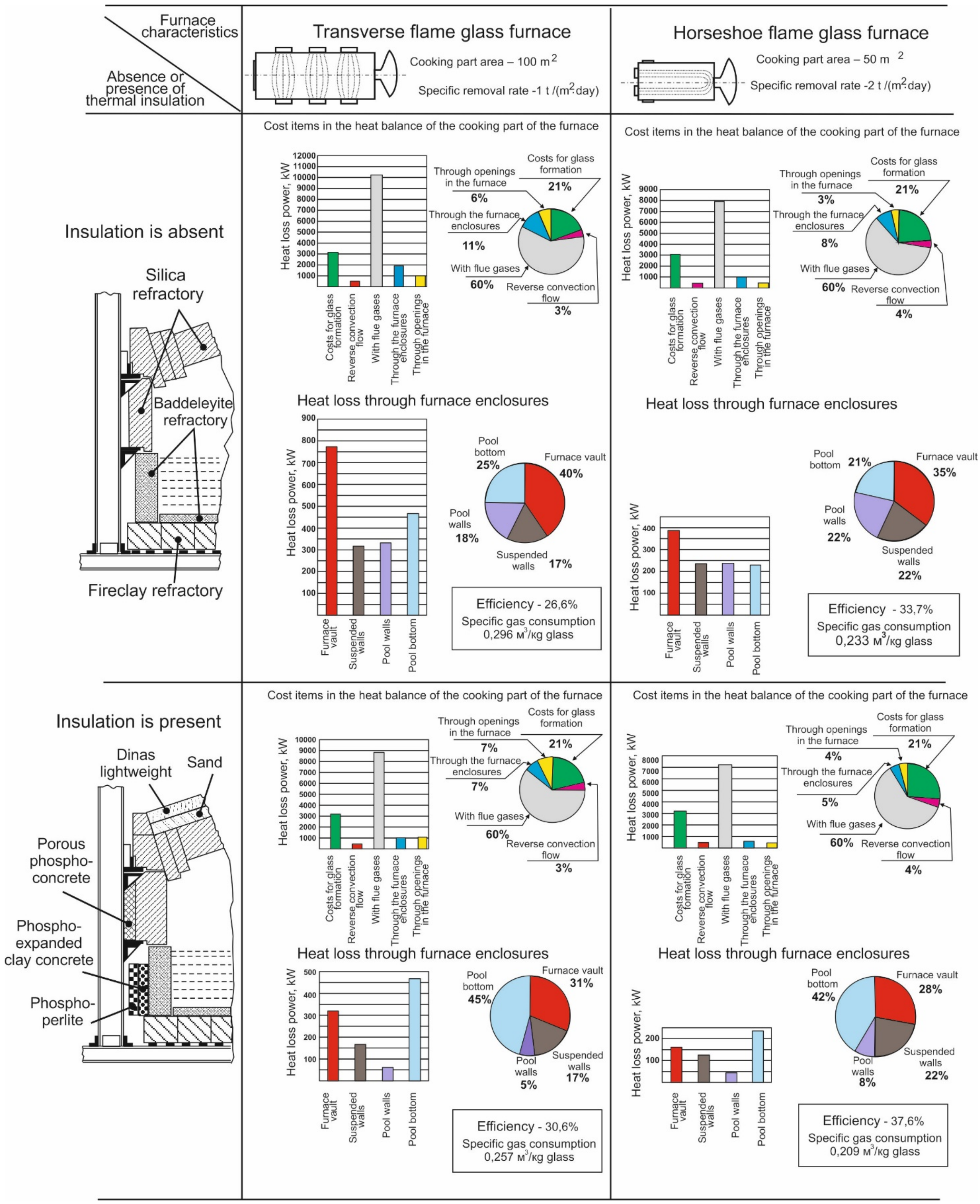

Fig. 1. Diagrams of balances of glass boiling furnaces

The use of thermal insulation of other areas of the furnace gives a much lower effect. According to the final result, the effectiveness of thermal insulation of the remaining three sections of the furnace with available thermal insulation materials is approximately the same. With simultaneous thermal insulation of all these areas with an insulation thickness of 10 cm, the final result is the value obtained with thermal insulation of only the vault.

In addition, the nature of the change in the curves of gas flow reduction and efficiency growth depending on the thickness of the thermal insulation for the vault is characterized by a rapid approach to the asymptotic value, for the rest of the sections – by a slow one. In the latter cases, the desired effect can be achieved with a significant thickness of the thermal insulation layer (Fig. 2).

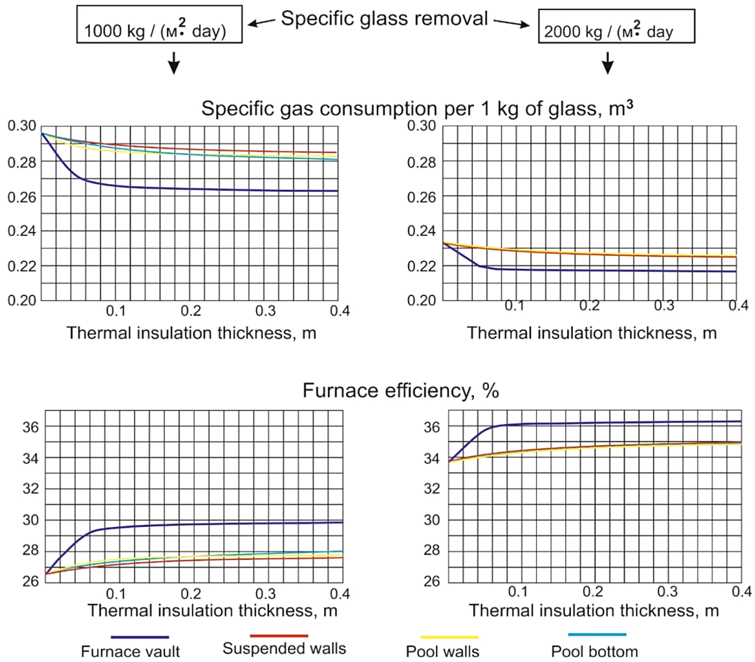

Fig. 2. The effectiveness of thermal insulation of individual sections of furnaces

Increasing the air heating temperature in the regenerators reduces the specific gas consumption per 1 kg of glass and increases the efficiency of the furnace. Thus, when the air temperature increases from 700 to 1200 °C in a non-insulated furnace with low specific removal, gas consumption can be reduced from 0.41 to 0.27 m^3/kg, and the efficiency can be increased from 21 to 34 %. For a heat-insulated furnace with a high specific removal of glass mass, the gas consumption was reduced from 0.28 to 0.19 m^3/kg, and the efficiency increased from 31 to 47 %. For the rest of the furnaces, the indicated indicators occupy intermediate values. Thus, the increase in air heating temperature significantly increased the energy efficiency of the heating unit. Increasing the air heating temperature by 100 °C increases the efficiency by 26–32 % (Fig. 3).

The addition of additional eclectic heating of the furnace showed a significant increase in the energy efficiency of the heat engineering unit. With an increase in the share of electricity input for heating the furnace, the total specific energy consumption for boiling glass decreases along a certain concave curve.

This value consists of two components: the amount of electrical and thermal energy (Fig. 4).

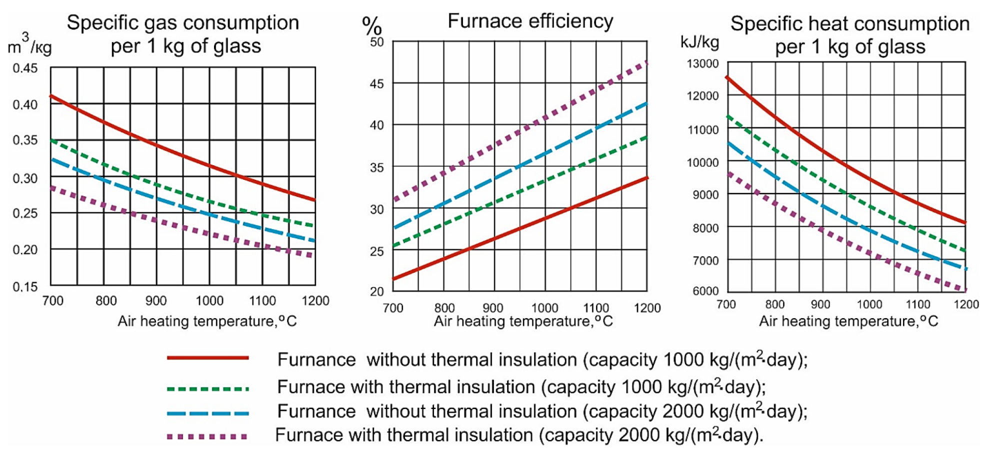

Fig. 3. The influence of the air heating temperature on the technical and economic parameters of the glass furnace

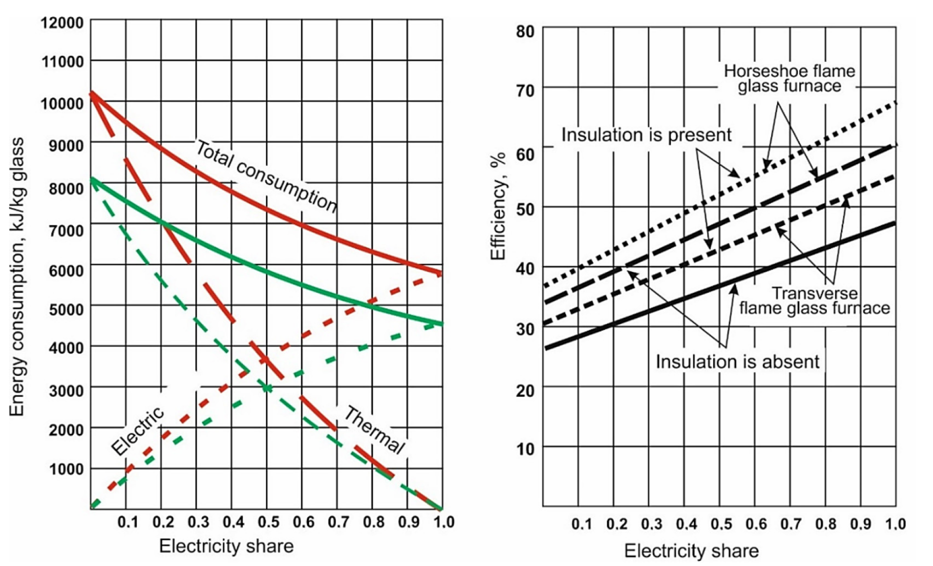

Fig. 4. The effect of additional electric heating on the technical and economic parameters of the glass furnace

Having analyzed the data of the conducted analysis, it can be stated that the most effective, from the point of view of increasing the energy efficiency of the glass furnace, is the introduction of additional electric heating for the furnace with a low specific removal of glass mass and without thermal insulation. A slightly lower efficiency of additional electric heating is characteristic of furnaces with high specific removal of glass mass and sufficient thermal insulation. The indicators of furnaces with low specific removal of glass mass (transverse flame) with thermal insulation and with high specific removal of glass mass (horseshoe flame) without thermal insulation occupy an intermediate value.

With an increase in the share of electricity input for heating, the overall efficiency of the furnace increases almost in a straight line. From the point of view of increasing the efficiency, the most effective is the introduction of electricity in the case of a furnace with a high specific removal and with sufficient thermal insulation. The efficiency of additional electric heating is somewhat lower when using a furnace with a low specific removal of glass mass and without thermal insulation. Thus, the introduction of every 10 % of additional electric heating instead of gas heating increases the efficiency of the furnace by 2–3 %. After analyzing the research data, it is possible to come to the conclusion that it will be optimal to use electric heating in the amount of 20–30 % in addition to the heat received during the combustion of gas fuel.

Limitations. The productivity of the furnace is 100 t/day, the specific removal of glass mass is 1000–2000 kg/(m^2·day), the design of the furnace for the furnace is with transverse and horseshoe-shaped flame development, the thickness of the thermal insulation layer is up to 0.4 m, the air heating temperature is 700–1200 °C.

The conditions of martial law in Ukraine affected the time management of research and increased the time it took to conduct it.

The obtained results will be used for conducting research on high-temperature glass-making processes, developing furnace designs, and establishing optimal parameters for the technological process of manufacturing glass products.

4. Conclusions

Computer modeling of thermal processes at the level of heat balance of the boiling part of the glass furnace was carried out. However, recommendations were made regarding measures to increase the technical and economic performance of glass furnaces. Thermal insulation of the vault will increase the efficiency of the furnace by 2–3 %. Thermal insulation of the remaining parts of the furnace in total will also increase the efficiency up to 3 %. Taking into account the great manufacturability of vault insulation measures, minimum capital costs, minimal material consumption, the vault insulation measures should be in the first place. Insulation of other areas of the furnace can be performed during the cold repair of the furnace.

An increase in the temperature of the air used for fuel combustion by 100 °C increases the efficiency of the furnace by approximately 3 %. However, such a measure is associated with an increase in the volume, and most importantly, the height of the nozzle of the regenerator. Therefore, such a measure can be implemented with a complete reconstruction of the furnace installation.

The introduction of additional electric heating reduces the total energy costs, and at the same time, the introduction of every 10 % of additional electric heating increases the efficiency of the furnace by 2–3 %. Additional electric heating improves many other aspects of glassmaking. Therefore, it can be recommended in the amount of 20–30 % of the total heat consumption. The analysis of the obtained results showed a fairly good convergence, which indicates the acceptable adequacy of the models.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

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