Methodological bases of optimization of thermal insulation structures of glass furnaces

D V Beknazarian¹, G E Kanevets² and K V Strogonov³

¹The group of companies "Vokenergomash", Russia, 603032 Nizhny Novgorod, Pamirskaya 11 AD
²National Technical University "KHPI", Ukraine, 61002 Kharkov, Kirpicheva 2
³National Research University "MPEI", Russia, 111250 Moscow, Krasnokazarmennaya, 14
david Beck@mail.ru

Abstract. In the construction of modern bathrooms of flaming glass furnaces, glass resistant refractory materials of high quality and a variety of thermal insulation materials are used, which are compounded into multi-layer thermal insulation panels, reducing heat losses. However, increasing the temperature of wall bars when applying thermal insulation sharply reduces their service life due to high-temperature physical and chemical corrosion. Such a contradiction and a wide range of insulation products, as well as various modes of glass melting and intensity of forced cooling of the outer lateral surface of the furnace requires the choice of an optimal set of thermal insulation materials under the chosen conditions of furnace operation to ensure maximum operating life of the unit with maximum efficiency.

1. Introduction
The process of manufacturing glass is a complex physical and chemical process, which involves a large number of complex, expensive heat exchange, dynamic, energy equipment. The main energy-technological installation in the vast majority of cases, due to high productivity (up to 400 tons of glass per day), is a large flaming glass furnace. This unit has a fairly low coefficient of efficiency (the best indicators are at the level of 60 %), which increases the requirements for the efficiency of the technological process. The most obvious way to reduce the cost part of the heat balance of existing furnaces is to reduce heat losses. Due to the large area of contact with the environment heated during operation of refractory materials of the furnace enclosure (bottom, walls, vault), a significant amount of heat is lost (from 1.3 to 5.6 kW per square meter) [1]. Smaller values correspond to the roof and bottom of the oven, and larger values correspond to the longitudinal walls of the cooking pool. The impact of high temperatures in the cooking zone has a destructive effect on the wall refractory bars (in the area of the flame space of the order of 1580-1600°C, in the area of molten glass 1480-1520°C), in addition, the bars are subject to abrasive wear by charge materials in the loading zone. These factors often determine the period of operation of refractory materials of the walls of the pool.

2. Relevance of optimization of thermal insulation structures of glass furnaces
As the object of research, we selected a continuous glass furnace similar in design [2, 3]. Table 1 shows the main geometric parameters of the unit under consideration.
In a number of articles of heat energy losses during the operation of a glass furnace, losses through side fences occupy the third largest position after heat losses with outgoing gases and produced glass, which makes it necessary to look for ways to reduce this article of losses while maintaining the quality of the technological process, focusing on the maximum extension of the service life of the furnace before cold repair. It is not possible to reduce heat from the glass mass produced, and reducing heat through the fence will reduce heat losses with outgoing gases. Extensive experimental data on the resistance of refractory bars and heat exchange in the system molten glass-refractory bar-external environment are given in the middle of the last century in the works of Zakharikov N A [4, 5]. However, in modern furnaces, in comparison with these works, thermal insulation of the side fence is widely used due to the appearance of refractory materials that are more resistant to the effects of molten glass.

Table 1. Geometrical and main technological parameters of the furnace

| Name                                           | Amount, mm |
|------------------------------------------------|------------|
| 1. Height from the level of the hearth to the skew brick | 2550       |
| 2. Length of the glass-melting tank             | 13750      |
| 3. Width of the glass-melting tank              | 8600       |
| 4. Thickness of fire-resistant bar – the cooking area | 250        |
|                                                | 200        |
| 5. Minimum remaining thickness of the fire-resistant bar at the time of stopping the furnace | 40         |
| 6. Height of the blowout zone                    | 400        |
| 7. Height of the nozzle unit                     | 1350       |
| 8. The thickness of the wall-mounted layer of molten glass (the temperature of which is slightly lower than the melt temperature away from the pool fence) | 50         |
| 9. Seconds fuel consumption, m3/s                | 0.366      |
| 10. The flow rate of the combustion air, m3/m3   | 9.27       |
| 11. Air excess factor                            | 1.1        |
| 12. The productivity of the furnace, kg/s       | 3.241      |

Table 1 shows the main technological parameters of the furnace and the articles of the heat balance of the furnace. The method of calculating the items of heat arrival and consumption in the heat balance of a glass-fired furnace is given in [6, 7]. The heat balance equation in General is more convenient to make in kilojoules per kilogram of technological product (kJ/kg or kW), it has the form [8]:

\[
Q_{c.e.f} + Q_{f.h} + Q_{h.o} + Q_{h.m} = Q_{h.p} + Q_{h.w.g} + Q_{l.e} + Q_{l.c} + Q_{u.l}
\]  

(1)

Table 2. Items of the heat balance of the investigated glass furnace bath

| Name of the income item          | kW     | %     | Name of the expenditure item | kW     | %     |
|---------------------------------|--------|-------|-------------------------------|--------|-------|
| Chemical energy of fuel, \(Q_{c.e.f}\) | 12888.29 | 64.01 | Heat of the process product, \(Q_{h.p}\) | 7376.83 | 36.63 |
| Fuel heat, \(Q_{f.h}\)          | 12.09  | 0.06  | Heat of waste gases, \(Q_{h.w.g}\) | 9973.70 | 49.53 |
| Heat of the oxidizer, \(Q_{h.o}\) | 7097.05 | 35.24 | Heat loss from incomplete combustion, \(Q_{l.c} = Q_{c.u}\) + mechanical underburning, \(Q_{m.u}\) | 257.77 | 1.28  |
|                                  |        |       |                                |        |       |
| Heat of initial technological materials, \(Q_{h.m}\) | 139.83 | 0.69  | Heat loss to the environment, \(Q_{l.e}\) | 1524.7 | 7.57  |
|                                  |        |       |                                |        |       |
|                                  |        |       |                                |        |       |
|                                  |        |       |                                |        |       |
| Total                           | 20137.26 | 100  | Total                         | 20137.26 | 100  |
|                                  |        |       |                                |        |       |
Corrosion of refractory bars of the longitudinal walls in zones download and melting greatly increases the amount of heat loss through the fences of the furnace, due to the reduced thickness of refractory boards to a minimum, capable of trouble-free operation of the object (the residual thickness of the bars is about 40 mm). Therefore, the calculation of the rate of corrosion of refractory bar by high-temperature molten glass, and as a result, the calculation of the dynamics of increasing heat losses are important components in the compilation of the thermal balance of the unit. The calculation of the rate of corrosion of refractory bars of the side fence of the furnace was performed in accordance with the method described in [9].

An important component of the furnace enclosure is high-performance thermal insulation [10], as well as a method for cooling the external surface of the pool [11-13] to prevent premature corrosion wear of refractory bars that come into contact with the molten glass.

Having the data set of geometric parameters and operating modes of the furnace, corrosion rate of refractory bars of high-temperature melt glass paste, it is possible to optimize multilayer insulation construction of glass furnace (HICGF) that will minimize heat loss into the environment through these fences with a maximum length of campaign (hours of work) of the furnace.

Optimization is one of the main tools for improving the efficiency of energy technology installations and equipment [14].

Figure 1 shows the stages of the hardware lifecycle [15].

Optimization of elements of thermal insulation structures of glass furnaces, which are an element of the fence, is applied at two main stages of the life cycle of HICGF:

1) in the design optimization of new HICGF (stage 3);
2) with optimal replacement of worn-out HICGF (stage 5.4) during their operation.

According to Fig. 1, when performing these types of optimization, all economic costs at the main stages of the life cycle, namely: research (stage 1), construction (stage 2), design (stage 3), production (stage 4), operation (stage 5) and liquidation (stage 6) of the HICGF, must be taken into account when forming the efficiency criterion for evaluating the optimal HICGF.

The facts that characterize the relevance of optimization of the HICGF are described below.
3. Basic concepts of optimization of thermal insulation structures of glass furnaces

In the field of chemical technologies and energy technologies interest in computational experiment was already shown in the last third of the twentieth century [15, 16, 19-21, 24]. However, at that time, its implementation was significantly limited by the capabilities of computer technology. Currently, the computational experiment is widely used in fundamental and applied research, as well as in the design of production facilities, including energy technology [14, 17, 18, 22, 24, 25]. Computational experiment in a broader, industrial sense – a new technology for the complex of works on the creation and functioning of an object at all or the main stages of its life cycle. A computational experiment in the narrow sense is the creation of mathematical models of the object under study and the subsequent study of this object using computer technology. It is based on the triad "mathematical model of an object-modeling algorithm-computer calculation program".
An example of this is the optimization computational experiment (OCE), which is effectively used in the process of creating and developing more efficient complex systems of various nature (technical, economic, social, political, and other systems).

Features of OCE.
1. The main feature of the OCE is the use of fundamental, systematic mathematical models, which are based on the results of numerous and versatile field experiments and theoretical research from different fields of knowledge (for example, engineering, mathematics, physics, chemistry, economics, etc.). This allows you to calculate a set of significant, including complex, characteristics of complex objects, predict their multi-factor behavior, and, accordingly, choose the best option of objects from a variety of possible ones.
2. The computational experiment reveals the degree of influence of the error of the initial data and elements of the mathematical model of the object on the error of finding the studied characteristics of the object. This makes it possible to specify more precisely the requirements for setting up new field experiments and for correcting and developing fundamental, systematic mathematical models.
3. When conducting the OCE drastically reduced development costs and significantly save time. This is provided by
   - multi-variant calculations,
   - the possibility of a more accurate technical and economic or other assessment of these options and the choice of the best one;
   - ease of modification of mathematical models for other research objects and their functioning conditions,
   - simplification and automation of the development of mathematical models of objects based on a generalized structural-modular approach.
4. A computational experiment can be performed when a full-scale experiment is either impossible or expensive. It is used, for example
   - when creating large technical systems such as main gas pipelines, hydroelectric power stations;
   - when predicting the consequences of adverse events such as an explosion of a nuclear reactor or an atomic bomb;
   - when predicting the consequences of changes in the country's socio-economic structure and many other cases.

In [14], six main stages and six components of the OCE are identified:
1. Selection or development of criteria for the effectiveness of the object.
2. Forming or creating a mathematical model of the object.
3. Selection or development of a method for searching for the extremum of the efficiency criterion.
4. Selection, development or synthesis of an algorithm and an object optimization program.
5. Conducting the first part of the optimization computational experiment: optimizing computer calculations.
6. Conducting the second part of the optimization computational experiment: processing optimization results, analyzing them and forming conclusions.

4. Principles of optimization of thermal insulation structures of glass furnaces
The OCE is a tool for optimizing the thermal insulation structures of glass furnaces.
In relation to our task for conducting OCE it is necessary to develop and implement the following:
1. Performance criteria HICGF.
2. Mathematical models of HICGF.
3. Methods of searching for the extremum in the optimization of the HICGF.
4. The algorithm for project optimization of the HICGF (PO-HICGF algorithm).
5. The software of project optimization of TCSP (software PO-HICGF).
6. Methodological bases of computational experiment for design optimization of new and optimal replacement of worn-out HICGF.
7. Conducting an OCE for the purpose of predicting the development of software on the basis of an optimization computational experiment in the near and long term.

A feature of the implementation of the mathematical model software is a great time any one option software necessary to ensure the required accuracy of the calculation, as well as a large dimension optimization problem. At the same time, the use of known direct and decomposition methods, as well as methods for optimizing multi-factor problems, becomes difficult or even impossible.

In this situation, in our opinion, the problems that have arisen can be solved by applying a new phenomenological heuristic-evolutionary approach (PHEA) by Kanevets G.E. [14, 17 – 19, 22, 23] when optimizing complex systems, which belongs to the class of evolutionary optimization methods.

The ideology of the phenomenological heuristic-evolutionary approach was formulated in the 70th years of the twentieth century by academician Kanevets G.E. and was first implemented by him, his disciple professor Berlin M.A. and their employees at the all-Union state University research and design Institute VNIPInazpererabotka when creating and operating an industry-wide computer-aided design system for optimal gas processing (gas-gasoline) plants. Such optimal plants are designed, built and operate in the Tyumen region, the Volga region and other regions of Russia, as well as in the Middle East. In the future, the phenomenological approach was used in various industries.

We have transformed the generalized scheme of the PHEA implementation taking into account the specifics of the task being solved.

This method uses the following basic heuristic-evolutionary procedures:

1. Select some initial mode of operation of the system in question, based on the experience and intuition of the calculator.
2. Using the algorithm for synthesizing the topology of complex circuits, an adjacency matrix of the ETS topology is formed with its reality check.
3. The calculation of the thermal state of the HICGF is made.
4. Under these operating conditions are optimized, the elements of the system. In simple cases, direct methods for finding the extremum are used, and for large complexity and size of the optimization problem, we use piecemeal heuristic-evolutionary procedures.
5. Technical and economic analysis of the system is Carried out. The elements that make the most significant contribution to the system efficiency criterion are determined.
6. To reduce the "weight" of these elements in the system's performance criteria, mode and design technical and economic and other heuristics are used, which change the operating mode and characteristics of the HICGF in order to improve its performance criteria.
7. The evolution of modes and equipment to the optimum is ensured.
8. The calculation is repeated from point 3.

Thus, when implementing the phenomenological heuristic-evolutionary approach, four subsystems of the components of the process of optimization of the HICGF are developed:

1. Subsystem for forming modes (SFM).
2. Subsystem of heuristic-evolutionary optimization of the object (SHEOO).
3. Service Subsystem (SSub).
4. Subsystem of information support (SIS) including databases.

Subsystems of SFM, SHEOO, SSub, and SIS are invariant in principle with respect to the extremum search method (optimization method) and can therefore be used when using other optimization methods for complex ETS.

In this case, the SHEOO subsystem only serves to limit the search area for the technical and economic optimum and therefore may not be available.

The generalized functional scheme retains its integrity and only changes the quality.

To form the structure of methodological, information and software for complex optimization [14] of the glass furnace enclosure (object), it is necessary to implement the following 19 stages of work (figure 2):
Figure 2. Structure of synthesis of methodological, information and software for complex optimization of modes of complex technical systems when fixing their topology.

*Level 1* – system analysis; *Level 2* – mathematical modeling; *Level 3* – programming; *Level 4* – computational and theoretical analysis

1. Create system classifications of calculation and optimization objects (ETS schemes, mode parameters, main types of equipment, objects of routine design).
2. Create system classifications for object calculation types and establish a hierarchy of these calculations.
3. Create an ideology of complex object optimization (COO).
4. Develop generalized structures for forming regimes.
5. Create a database of thermal properties of substances.
6. Develop General (unified) and specific modules for calculating the processes of mass transfer, heat transfer, hydro-mechanics, design, economic, service calculations, as elements of generalized structures for calculating the main types of equipment.
7. Establish the hierarchy of the entire complex of generalized structures, calculation modules, and algorithms.
8. Develop algorithms for generating modes. Create a database of modes.
9. Develop algorithms for calculating and technical and economic optimization of the main types of equipment. To form a database about the equipment and economic indicators.
10. Develop methods and algorithms for refined technical and economic optimization at all levels.
11–13. Perform programming of the algorithms listed in points 8-10.
14-17. Develop complex software for equivalence of mathematical models and algorithms: generalized algorithms and equivalence programs (14); equivalent models and calculation modules (15); equivalent algorithms of the COO (16); programs corresponding to equivalent algorithms (17).
18. Conduct a set of optimization calculations on a computer.
19. Conduct a computational and theoretical analysis of the results of calculations and develop recommendations for the development of the methodological basis for the complex optimization of the energy system COES.

5. Conclusion
The main concepts and principles of optimization are considered. The article substantiates the application of an optimization computational experiment and a phenomenological heuristic-evolutionary approach to optimizing the thermal insulation structures of high-performance bathrooms of flaming glass furnaces. The thermal balance of a glass-fired furnace is compiled in the case of using the optimal variant of the HICGF. The use of this method to optimize the HICGF of glass furnaces allows you to extend the working life of the side fence of the furnace, with minimal heat losses to the environment.

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