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TARGET FUNCTIONS OF OPTIMIZATION OF HEAT RECOVERY SYSTEMS

Summary. *The expenditure of energy resources on industrial production in Ukraine, as a rule, significantly exceeds the world average, therefore, the creation of effective equipment for power plants of different types is an important and urgent problem. A necessary condition for increasing the efficiency of equipment is thermodynamic optimization. Its main problems* *include the selection of optimization target functions that can be used to solve optimization problems.*

The aim of the work is to develop the basic principles for constructing optimization target functions necessary for solving optimization problems in heat recovery systems.

The results of the analysis of the target functions of optimization of power plants, the construction of which is based on the use of exergy methods, are presented. Based on the analysis, the main principles for constructing the indicated functions necessary for solving optimization problems in heat recovery systems have been developed. An integrated approach to the construction of target functions is proposed. This approach allows to evaluate its performance from various positions when analyzing the efficiency of heat recovery equipment. As optimization target functions, criteria that are highly sensitive to changes in the design and operation modes of the heat recovery system and allow you to establish the necessary functional dependencies are proposed. An example of the application of the optimization target functions the parameters of a contact plate air heater included in the combined heat recovery system of a boiler plant designed to heat water and blast air is given.

Key words: *objective function, optimization, heat recovery.*

Relevance. The problem of saving fuel and energy resources affects more and more manufacturing enterprises in Ukraine. The expenditure of energy resources for industrial production in the country, as a rule, significantly exceeds the world average, therefore, the creation of effective equipment for power plants of various types is an important and urgent problem. A necessary condition for increasing the efficiency of equipment at the stage of developing technical solutions is thermodynamic optimization. Among its main probles is the selection of optimization target functions that can be used to solve optimization problems.

Analysis of recent research and publications. In recent years, in world practice, efficiency analysis and optimization of various power plants are increasingly carried out using exergy analysis methods [1-8]. Thus, in [Valencia G., 2019], for the various heat recovery schemes of engines using natural gas based on the organic Rankine cycle, the results of energy and exergy analysis are presented. A thermodynamic model for evaluating the characteristics of each circuit is proposed, and the optimal heat recovery scheme and its optimal operational characteristics are found. The work [Fontalvo A., 2017] is devoted to exergy analysis and thermodynamic optimization of low-quality heat sources for generating electricity, which can be converted into mechanical energy and electricity using small-scale organic Rankine cycles. In the work [Sahin A., 2014], it was noted that using the methods of exergy analysis it is advisable to determine those stages of the technological process for which optimization is possible.

In the majority of the works under consideration, exergy efficiency and exergy losses are used as objective optimization functions. Using only the exergy approach to the analysis of the efficiency and optimization of power plants often does not reflect some important points of the processes under study. Therefore, the works [Fialko N., 2016], [Fialko N., 2017], [Fialko N., 2018], [Fialko N., 2019] are devoted to the application of the exergy approach to the creation of complex methods combining exergy analysis methods with other modern research methods. Further work in the direction of improving the processes of optimization of power plants, in particular, heat recovery systems will significantly increase their efficiency.

The purpose of the work and research problems. The aim of the work is to develop the basic principles for constructing optimization target functions necessary for solving optimization problems in heat recovery systems.

To achieve this aim it is necessary to solve the following tasks:

- to analyze the various target optimization functions for power plants;

- to develop the basic principles for constructing optimization target functions that can be used in solving optimization problems for heat recovery systems;
- in accordance with the basic principles, to propose an approach to the construction of target optimization functions, which allows, when analyzing the efficiency of heat recovery equipment, to evaluate the operation of the system simultaneously from several positions;
- to propose criteria as optimization functions that are highly sensitive to changes in the design and in operation modes of the heat recovery system and allow establishing the functional dependences necessary for optimization.

Materials and research methods. Integrated approaches based on methods of exergy analysis were used to develop the basic principles for constructing target functions for optimizing heat recovery systems.

Research results and discussion. Modern heat recovery systems are, as a rule, part of complex power plants in which various types of energy are used. For the quantitative reflection of the interactions occurring in such facilities, a mathematical model is needed, which should:

- to reflect the physical characteristics of the conversion of various types of energy in a power plant under various modes of its operation;
- to provide the opportunity to obtain a formalized procedure for modeling, analysis and solving problems of energy conservation;
- to provide verification of the presence or absence of emergent properties of the installation and display its interconnectivity;
- to provide the ability to solve optimization problems both for the entire installation, and for its individual elements.

To obtain the indicated mathematical model as applied to heat recovery systems, the use of the concept of an exergy analysis method can be considered thermodynamically justified. In accordance with this concept, a full analysis of complex real processes in heat recovery systems should include:

- material balance, allowing to determine the amount of working fluid involved in each individual process;
- heat balance, with the help of which the amount of heat removed or supplied in each process is determined;
- exergy balance, which allows to determine the effectiveness of each process from the point of view of obtaining the most useful work, as well as the loss of performance in each process caused by one or another real irreversibility of the processes;
- search for optimization target functions using the results of solving the system of balance equations.

Currently, when evaluating the performance of power plants, including heat exchange equipment, as a rule, one approach is used: thermodynamic, heat engineering, technological, exergy, economic. In the exergy approach, various variants of the exergy coefficient of efficiency are most often used as optimization target functions. It includes either total exergy flows at the input and output of the system, or useful and expended exergy, or exergy that does not undergo qualitative transformations in the system, and so on. The exergy coefficient of efficiency, determined using one of these methods, often does not reflect some important points of the studied processes. For example, it does not take into account the purpose of the process, the ambiguity in the interpretation of beneficial effects and expenditure. With its help, it is impossible to localize exergy losses and determine the causes that caused them. Therefore, it is advisable to use integrated approaches in assessing the performance of power plants. Such an approach is the exergoeconomic approach, when applying it, the combination of price indicators of exergy and total cost indicators of capital investments are usually chosen as the objective optimization functions.

However, the exergoeconomic approach does not take into account information about the heat engineering and technological properties of the system.

To construct optimization target functions necessary for solving optimization problems in heat recovery systems, the following principles have been developed that combine the basic requirements for these functions:

- using the optimization target functions, it is necessary to evaluate the operation of the heat recovery system simultaneously from several positions;
- target optimization functions should be highly sensitive to changes in the design and operation modes of the heat recovery system;
- these functions should provide the ability to obtain the necessary functional dependencies on the structural and operational parameters of the system;
- the target optimization functions should serve to verify the emergent properties and interectivity of the heat recovery system.

Evaluation of the operation of heat recovery systems with thermodynamic, heat engineering and technological positions is possible using an integrated approach to the construction of target optimization functions. Such an approach involves the inclusion in the target functions of optimizing the main characteristics of the system, in particular, exergy characteristics that are highly sensitive to changes in operating and design parameters. Based on the above principles of construction, exergy criteria are proposed as target optimization functions for heat recovery systems of boiler units and glass melting furnaces, as well as their individual elements, which include exergetic losses E, heat power Q and specific material consumption. Using these criteria, it is possible to evaluate the operation of the heat recovery system from various perspectives, to establish the necessary functional dependences on the parameters of the system, for example, based on statistical methods of the theory of experimental design, and determine their optimal values. The use of optimization algorithms for the theory of experimental design, as well as taking into account the characteristics of power plants and a specific heat recovery scheme, allows, based on the values of the optimal parameters, to find the optimal areas for changing the parameters.

An example of applying the optimization target function to optimize the parameters of a contact plate air heater is given. The air heater is included in the combined heat recovery system of the boiler plant, designed to heat water and blast air. As an target optimization function, a heat-exergy efficiency criterion was used $\varepsilon = E/Q$. Using the experimental design methods, functional dependences of ε were obtained on the width of the heater plate *a* and the height *b* for a fixed optimal distance between the plates *s* = 5,5mm for various values of the ambient temperature t_0. The minimum of the received functions corresponds t_0 the maximum efficiency of the air heater. The resulting dependencies are as follows:

$t_0 = -5^{o}C$

$\varepsilon = 0,89 - 4,07 \cdot 10^{-4}\, a + 1,07 \cdot 10^{-7} a^2 - 3,98 \cdot 10^{-4}\, b + 1,38 \cdot 10^{-7}\, b^2 + 2,32 \cdot 10^{-8}\, a\, b,$

$t_0 = 0^{o}C$

$\varepsilon = 0,58 - 3,54 \cdot 10^{-4}\, a + 1,19 \cdot 10^{-7}\, a^2 - 1,75 \cdot 10^{-5}\, b + 3,77 \cdot 10^{-9}\, b^2 + 2,43 \cdot 10^{-9}\, a\, b,$

$t_0 = 5^{o}C$

$\varepsilon = 0,42 - 2,49 \cdot 10^{-4}\, a + 8,54 \cdot 10^{-8}\, a^2 - 7,90 \cdot 10^{-6}\, b + 3,61 \cdot 10^{-10}\, b^2 + 8,84 \cdot 10^{-10}\, a\, b.$

Using one of the optimization algorithms of the theory of experimental design, namely, the method of canonical transformations, allows you to get a visual representation of the geometric interpretation of the surface of functions in the minimum. The equations are representable in canonical form:

$t_0 = -5^{o}C$

$\varepsilon - 2,73 \cdot 10^{-1} = 1,42 \cdot 10^{-7}\, a^2 + 1,04 \cdot 10^{-7}\, b^2,$

$t_0 = 0^{o}C$

$\varepsilon - 3,03 \cdot 10^{-1} = 1,19 \cdot 10^{-7}\, a^2 + 3,79 \cdot 10^{-9}\, b^2,$

$t_0 = 5^{o}C$

$\varepsilon - 2,12 \cdot 10^{-1} = 8,54 \cdot 10^{-8}\, a^2 + 3,37 \cdot 10^{-10}\, b^2.$

The interpretation of the response surface in the region of the minimum in all cases is an ellipsoid depression, and the contour curves in the region of the minimum for various values of the response function are ellipses. The coordinates of the centers of the contour curves are the optimal values of the parameters *a* and *b*. The values of these coordinates and the corresponding values of the heat-exergy criterion are as follows: at t_0 = –5^o*C* - *a* = 1770mm, *b* = 1290mm, ε = 0.270; at t_0 = 0^o*C* - *a* = 1460 mm, *b* = 1850 mm, ε = 0.303; at t_0 = 5^o*C* - *a* = 1410mm, *b* = 2000mm, ε = 0.330. In fig. 1 shows a graph of the dependence and the corresponding contour curves for the air heater under study at ambient temperatures t_0 = 5^o*C*.

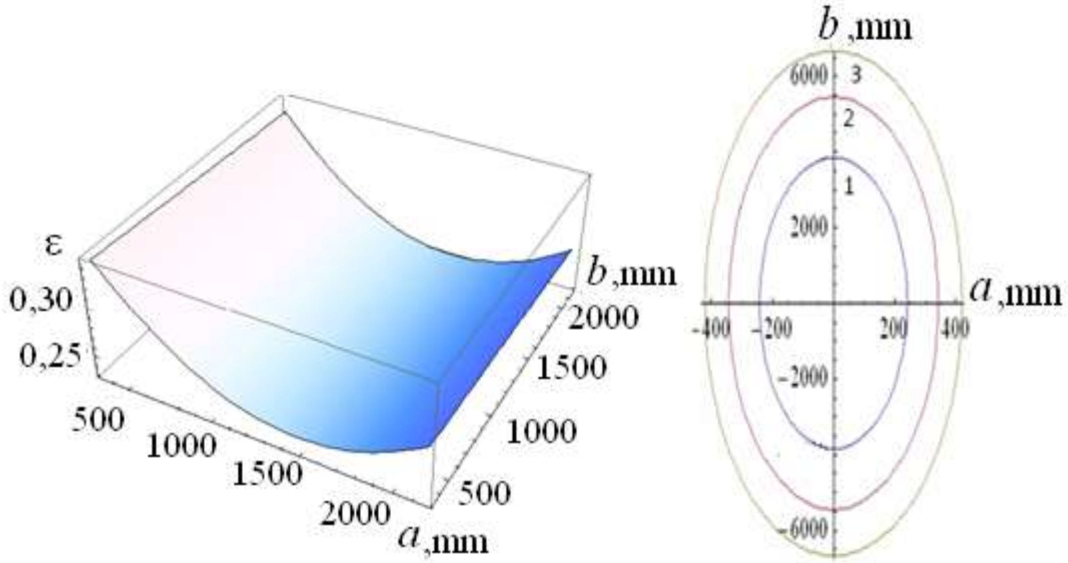

Fig. 1. The dependence of the heat-exergy criterion of ε on the width of the plate *a* and height *b* at *s* = 5,5mm for t_0 = 5^o*C*; and contour curves in the optimum region: 1 – ε =0,335, 2 – 0,340, 3 – 0,345.

The distance between the contour curves of the response surface within the specified change in the response function and the distance of the curves from the center for parameter *b* is significantly greater than parameter *a*. A slight change in the function of the hail with a change in the corresponding parameter allows us to expand the interval of its change during the design of the heat-exchange surface. Whereas a significant change in the function of the hail with a sufficiently small change in the parameter makes it necessary to adhere to the exact values of the optimal parameters when designing. This means that the permissible optimal intervals for changing the parameter b can be extended. For the presented case, the optimal intervals for changing the parameters are:

1300mm $\leq a \leq$ 1500mm; 1500mm $\leq b \leq$ 2000mm;

5mm $\leq s \leq$ 6mm.

The scientific novelty of the results. For the first time, using an integrated approach based on exergy analysis methods and exergy criteria, the basic principles for constructing optimization functions necessary for solving optimization problems in heat recovery systems have been developed.

Practical value. As target optimization functions for heat recovery systems of boiler units and glass melting furnaces, as well as their individual elements, exergy criteria have been proposed, with the help of which the optimal areas of variation of operating and structural parameters are determined.

Conclusions

1. The analysis of the target functions of optimization of power plants, the construction of which is based on the use of exergy methods.
2. On the basis of the analysis, the basic principles of constructing target optimization functions necessary for solving optimization problems in heat recovery systems have been developed.
3. A comprehensive approach to the construction of target optimization functions is proposed, which allows, when analyzing the efficiency of heat recovery equipment, to evaluate the operation of the system from various positions.
4. As target optimization functions, criteria are proposed that are highly sensitive to changes in the design and operation modes of the heat recovery system and allow you to establish the necessary functional dependences on the system parameters to find their optimal values.

5. An example of applying the optimization target function to optimize the parameters of a contact plate air heater is given. The air heater is included in the combined heat recovery system of the boiler plant, designed to heat water and blast air.

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