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OPTIMIZATION OF GEOMETRIC PARAMETERS AND ANALYSIS OF EXERGY EFFICIENCY OF HEAT RECOVERY UNITS GLASS FURNACES

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Abstract. *The paper presents the results of optimization of the geometric parameters of the heat exchange surface of water and air-heating heat exchangers of glass-making furnaces and an analysis of their exergy efficiency. Ensuring the efficient operation of heat recovery units in various thermal circuits is an urgent problem of heat power engineering. The aim of the work is to establish the optimal areas of the geometric parameters of the heat exchange surface of heat recovery units of glass-melting furnaces and to analyze their exergy efficiency. The paper presents the results of solving the tasks necessary to achieve the goal:*

- using statistical methods for planning the experiment, determine the levels of variation of the parameters of the geometric surface of heat transfer for the heat recovery units under study and calculate the values of the criteria for evaluating the efficiency at the points of the central orthogonal compositional plan;

- to obtain the regression equations for the investigated heat exchangers, to determine the optimal areas of change in the geometric parameters of the heat exchange surface and the corresponding exergy efficiency criteria.

To determine the optimal areas of geometric parameters of the heat exchange surface, a complex methodology is used based on the methods of exergy analysis and statistical methods of the theory of experiment planning. It has been established that when designing heat recovery schemes for heating water in heat supply systems and for heating blast air, heat recovery units with the following values of the areas of variation of the geometric parameters of the heat exchange surface can be used:

- the values of the area of variation of the distance between the panels for heat recovery units with a staggered and corridor arrangement of pipes in a bundle s_1 = 58.0-62.0 mm.

- the values of the areas of change in the diameter of pipes for a hot water heat exchanger with a corridor arrangement of pipes d = 41.0-43.0 mm and for an air heating heat exchanger with a staggered and corridor arrangement of pipes d = 29.0-31.0 mm.

- the use of the values of the ranges of change of other parameters is carried out taking into account additional technological factors.

It has been established that the exergy efficiency of hot water heat recovery units is in all cases higher than the exergy efficiency of air heating units. For hot water heat exchangers, the values of exergy criteria are lower than for air heating ones: k – 2.0 times, ε – by 7.5%, m_0 – 1.9 times. The expediency of using the investigated heat recovery units in heat recovery circuits of glass melting furnaces has been established, taking into account the results obtained and in the presence of certain technological factors.

The results obtained and further developments in the field of optimization of the operating parameters of heat recovery units for glass-melting furnaces will provide an increase in the efficiency of heat recovery equipment for power plants.

Key words*: exergy methods, experiment planning, heat recovery unit, optimal parameters*

Introduction. The development of efficient equipment for energy-saving heat recovery technologies is an important problem in the heat power industry. The use for this purpose of modern complex techniques based on a combination of exergy analysis methods, statistical methods of experiment planning theory, structural-variant methods, etc. allows solving the problems of optimal design of power plants and their individual elements. For elements of heat recovery systems of boiler plants, such studies have been carried out. However, there is a problem of optimizing the parameters and analyzing the exergy efficiency of the equipment of heat recovery systems of glass-melting furnaces. The use of these techniques to optimize the parameters of heat recovery units included in the heat recovery systems of glass melting furnaces makes it possible to ensure their efficient operation. Considering the above, studies aimed at optimizing the heat recovery equipment of glass furnaces are relevant.

Analysis of recent research and publications. In the study of the exergy efficiency of installations of various types, the exergy efficiency of both installations as a whole and their individual elements is most often assessed by the loss of exergy, or exergy efficiency. For example, to analyze the efficiency of the boiler house in [1], the balance method of exergy analysis was used, with the help of which two main types of exergy losses associated with irreversible combustion of fuel and heat transfer are considered. Studies related to the analysis of exergy losses in individual elements of power plants are considered in many works. Thus, the purpose of work [2] is to establish, with the help of energy and exergy studies, individual components of a nuclear power plant that have high losses of exergy. Work [3] is devoted to a detailed exergy analysis of all elements of a high-temperature combined cycle power plant. The system is analyzed from an exergy point of view on the basis of an exergoeconomic model. The main purpose of work [4] is to analyze the individual components of a power plant and identify the elements that have the greatest energy and exergy losses. In work [5], it is noted that with the help of exergy analysis methods it is advisable to determine those stages of the technological process for which optimization is possible. Work [6] compares various heat recovery systems in terms of exergy losses. To find the best system, an optimization algorithm is applied to all proposed cycles and the system with the highest exergy efficiency is determined. Optimization algorithms based on the use of techniques that use individual exergy characteristics do not allow a complete assessment of the thermodynamic perfection of the system. In the available publications, the exergy efficiency of installations is most often assessed only by the exergy efficiency. This approach does not reflect some important aspects of the processes under study. For example, the purpose of the process is not taken into account, there is ambiguity in the interpretation of beneficial effects and costs, and the impossibility of establishing the localization of exergy losses.

If integrated techniques are used to optimize heat recovery equipment, the efficiency of heat recovery technologies increases. This is demonstrated in [7, 8] devoted to the use of an integrated approach based on exergy analysis methods to study the efficiency and optimization of elements of heat recovery systems of boiler plants. However, the optimization of the parameters of the equipment of heat recovery systems of glass-melting furnaces has been insufficiently completed. Therefore, it is advisable to carry out studies devoted to the optimization of the geometric parameters of the heat exchange surface of heat exchangers of glass-melting furnaces using an integrated approach, including the methods of exergy analysis, statistical methods of experiment planning and exergy criteria of efficiency. Further research in the field of optimizing the operating parameters of heat recovery units for glass-melting furnaces will provide the necessary information for the development of optimal heat recovery schemes for power plants.

The aim of the work is to establish the optimal areas of the geometric parameters of the heat exchange surface of hot water and air-heating heat recovery units of glass furnaces and a comparative analysis of the efficiency of heat recovery units. This will allow the development of optimal heat recovery schemes for glass furnaces.

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

- using statistical methods for planning the experiment, determine the levels of variation of the parameters of the geometric surface of heat transfer for the heat recovery units under study and calculate the values of the criteria for evaluating the efficiency at the points of the central orthogonal compositional plan;

- to obtain the regression equations for the investigated heat exchangers, to determine the optimal areas of change in the geometric parameters of the heat exchange surface and the corresponding efficiency criteria.

Materials and research methods. The work considered hot water and air-heated panel heat exchangers included in the heat recovery systems of glass furnaces. A hot-water heat exchanger is used in circuits for heating water in heat supply systems, an air-heated one - in circuits for heating blast air. The hot water heat exchanger consists of three vertical modules, the hot water one - of two modules. The heat exchange part of each heat exchanger module is composed of sections in the form of tube panels with a staggered and corridor arrangement of tubes. The general direction of the heat carrier flows is countercurrent. The flow diagram of the heat carriers is cross-flow with one-pass gas movement and multi-pass movement of the heated heat carrier.

To determine the optimal areas of geometric parameters of the heat exchange surface of heat recovery units and analyze their exergy efficiency, a complex technique is used, including the methods of exergy analysis, statistical methods of the theory of experiment planning and the choice of exergy efficiency criteria, which are the target optimization functions. It is advisable to use such efficiency criteria, which combine the main exergy characteristics of heat recovery units. This makes it possible to evaluate the efficiency of heat recovery units from various positions: thermodynamic, heat engineering and technological. The following exergy criteria for assessing efficiency were used in the work: $k = E_{los}m / Q^2$, $\varepsilon = E_{los} / Q$ and $m_0 = m / Q$. Here E_{los} is exergy losses, m is mass; Q - heating capacity. The values of exergy losses Elos were calculated using the balance method of exergy analysis. The use of several criteria makes it possible to more accurately determine the optimal ranges of variation of the parameters of heat recovery units and to analyze their efficiency.

Research results.

Determination of the levels of variation of the geometrical parameters of the heat exchange surface for the investigated heat exchangers and the calculation of the values of the efficiency criteria at the points of the plan

The solution of the optimization problem for the heat recovery units under study includes obtaining functional dependencies of the target optimization functions from independent factors (regression equations). To obtain regression equations, statistical methods of experiment planning are used. In this study, the target optimization functions are the specified criteria for evaluating the effectiveness, and the independent factors are the parameters of the heat exchange surface of the hot water and air heating panel heat exchangers. These are the distance s1 between the panels in the direction transverse to the direction of the gas flow, the distance s2 between the pipes in the panel in the longitudinal direction with respect to the gas flow, and the value of the pipe diameter d. The main levels of variation of the parameters of the geometrical surface of heat recovery units have been determined (Table 1). The real requirements for the operational and design features of heat recovery units made it possible, when determining the main levels of variation for hot-water and air-heating heat recovery units, to take the same intervals of change in the geometric parameters of the heat exchange surface. For each of the objects under study, a planning matrix was built, in the construction of which an orthogonal central compositional plan was used. The criterion for the optimality of the design is the orthogonality of the columns of the planning matrix, which was achieved due to a specially selected stellar shoulder, the value of which is used to transform the quadratic factors and the free term of the regression equation. At each of the 15 points of the plan, the values of the performance criteria were obtained. As an example, the values of efficiency criteria at points of the plan for a hot water heat exchanger are given (Table 2).

1. The main levels of variation of the parameters of the geometric surface of heat recovery units

Variation levels	Geometric heat transfer surface parameters		
	s_1, mm	s_2, mm	d, mm
Main upper level	120,0	120,0	42,0
Main lower level	60,0	60,0	30,0
Zero level	90,0	90,0	36,0
Upper level of star points	126,5	126,5	43,3
Lower level of star points	53,6	53,6	28,7
Variation interval	30,0	30,0	6,0

2. Values of efficiency criteria at points of an orthogonal central compositional plan for a hot water heat recovery unit

№ plan point	Chess bunch			Corridor beam		
	k	ε	m_0	k	ε	m_0
1	0,643	0,329	1,96	0,712	0,341	2,14
2	0,735	0,332	2,32	0,841	0,345	2,39
3	1,270	0,358	3,53	0,912	0,360	2,48
4	1,315	0,359	3,58	0,937	0,351	2,71
5	0,580	0,309	1,82	0,609	0,319	2,03
6	0,661	0,311	2,09	0,698	0,321	2,31
7	1,198	0,358	3,29	0,749	0,340	2,32
8	1,190	0,349	3,41	0,778	0,334	2,39
9	0,911	0,345	2,62	0,751	0,348	2,22
10	0,969	0,338	2,82	0,823	0,329	2,53
11	0,581	0,309	1,90	0,690	0,331	2,08
12	1,268	0,361	3,49	0,821	0,342	2,39
13	0,959	0,349	2,72	0,826	0,350	2,41
14	0,868	0,334	2,54	0,681	0,309	2,21
15	0,911	0,346	2,62	0,752	0,308	2,31

When conducting experiments in each series of trials, the order of the experiments was randomized. The homogeneity of variances at each level of factors was assessed according to the Cochran criterion, the significance of the coefficients of the regression equations was checked by the Student's test, and the adequacy of the obtained equations to the data used was checked by the Fisher criterion.

Obtaining regression equations, determining the optimal areas of change in geometric parameters and the corresponding performance criteria

Regression equations were obtained for the investigated heat recovery units using the values of the efficiency criteria presented in Table 2. As an example, regression equations in code variables for a hot water heat exchanger are given.

Chess bunch:

$$k = 8{,}99\cdot10^{-1} + 2{,}53\cdot10^{-2}X_1 + 2{,}93\cdot10^{-1}X_2 - 4{,}17\cdot10^{-2}X_3 - 2{,}21\cdot10^{-2}X_{12} -$$

$$- 5{,}12\cdot10^{-3}X_{13} - 6{,}37\cdot10^{-3}X_{23} + 2{,}44\cdot10^{-2}X_{11} + 1{,}56\cdot10^{-2}X_{22} + 7{,}84\cdot10^{-3}X_{33};$$

$$\varepsilon = 3{,}41\cdot10^{-1} - 2{,}29\cdot10^{-3}X_1 + 1{,}91\cdot10^{-2}X_2 - 6{,}98\cdot10^{-3}X_3 - 1{,}88\cdot10^{-3}X_{12} +$$

$$+ 1{,}25\cdot10^{-4}X_{13} + 3{,}38\cdot10^{-3}X_{23} + 2{,}17\cdot10^{-3}X_{11} - 4{,}26\cdot10^{-3}X_{22} + 1{,}83\cdot10^{-3}X_{33};$$

$$m_0 = 2{,}62 + 9{,}62\cdot10^{-2}X_1 + 7{,}08\cdot10^{-1}X_2 - 7{,}27\cdot10^{-2}X_3 - 4{,}88\cdot10^{-2}X_{12} -$$

$$- 8{,}75\cdot10^{-3}X_{13} - 2{,}63\cdot10^{-2}X_{23} + 6{,}05\cdot10^{-2}X_{11} + 4{,}70\cdot10^{-2}X_{22} + 1{,}31\cdot10^{-2}X_{33}$$

Corridor bunch:

$$k = 7{,}43\cdot10^{-1} + 3{,}37\cdot10^{-2}X_1 + 5{,}95\cdot10^{-2}X_2 - 6{,}24\cdot10^{-2}X_3 - 2{,}20\cdot10^{-2}X_{12} -$$

$$- 3{,}48\cdot10^{-3}X_{13} - 9{,}77\cdot10^{-3}X_{23} + 2{,}78\cdot10^{-2}X_{11} + 5{,}85\cdot10^{-3}X_{22} + 4{,}83\cdot10^{-3}X_{33};$$

$$\varepsilon = 3{,}29\cdot10^{-1} - 2{,}59\cdot10^{-3}X_1 + 5{,}40\cdot10^{-3}X_2 - 1{,}34\cdot10^{-2}X_3 - 2{,}63\cdot10^{-3}X_{12} -$$

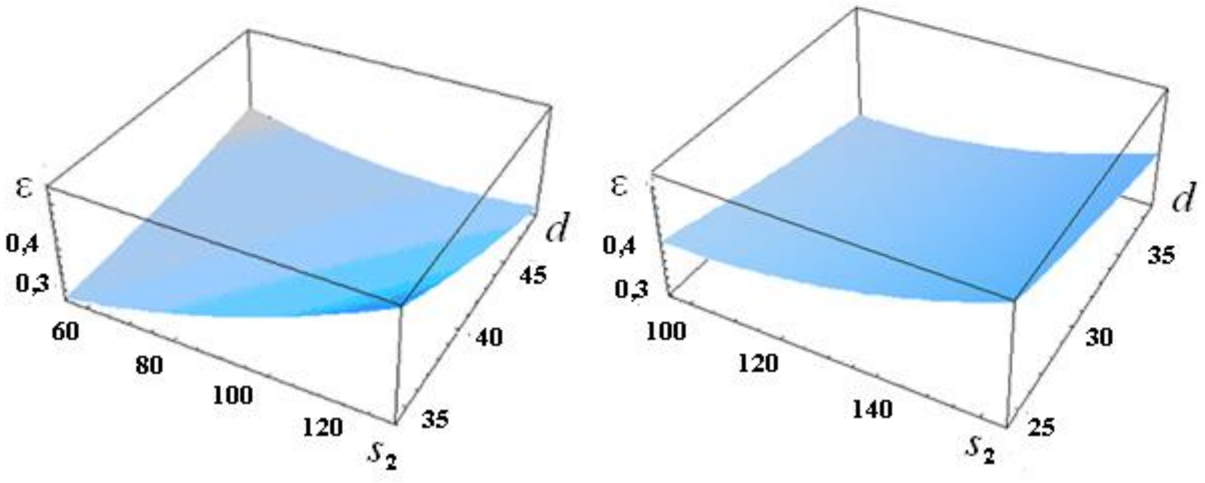
$$- 3{,}80\cdot10^{-4}X_{13} - 1{,}20\cdot10^{-4}X_{23} + 4{,}44\cdot10^{-3}X_{11} + 7{,}18\cdot10^{-4}X_{22} - 3{,}00\cdot10^{-4}X_{33};$$

$$m_0 = 2{,}25 + 1\cdot10^{-1}X_1 + 1{,}40\cdot10^{-1}X_2 - 9{,}36\cdot10^{-2}X_3 - 4{,}88\cdot10^{-2}X_{12} -$$

$$- 3{,}75\cdot10^{-3}X_{13} - 2{,}13\cdot10^{-2}X_{23} + 5{,}65\cdot10^{-2}X_{11} + 1{,}25\cdot10^{-2}X_{22} + 1{,}59\cdot10^{-2}X_{33}$$

The transition in the obtained regression equations from the code variables X_{ij} to the physical variables xij is carried out in accordance with the formula: $X_{ij} = (x_{ij} - x_{io}) / \delta_{ij}$, where xio is the zero level of variation, δij is the variation interval. Figure shows graphs of the most characteristic functional dependencies for the physical variables of the heat recovery units under study with a staggered arrangement of pipes in a bundle.

As a result of minimizing the obtained functional dependencies, the optimal values of the geometrical parameters of the heat exchange surface of the heat exchangers were determined. On the basis of the obtained optimal values, the optimal areas of variation of the geometric parameters and the criteria corresponding to the optimal values of the geometric parameters were determined (Tables 3, 4).



a *b*

Figure. Dependence of the heat-exergy efficiency criterion on the distance between the pipes in the panel s_2 and the diameter of the pipes *d* at the optimal distance between the panels s_1 = 60 mm (checkerboard bundle):

a - hot water heat exchanger; *b* - air-heating heat exchange

3. Optimal areas of variation of the geometric parameters of the heat exchange surface of heat recovery units

Criterion	Parameter	Hot water heat recovery unit		Air heating heat recovery unit	
		Chess bunch	Corridor bunch	Chess bunch	Corridor bunch
k	s_1, мм	58,0-62,0	58,0-62,0	58,0-62,0	58,0-62,0
	s_2, мм	70,0-74,0	57,0-61,0	58,0-62,0	58,0-62,0
	d, мм	37,0-39,0	41,0-43,0	29,0-31,0	29,0-31,0
ε	s_1, мм	58,0-62,0	58,0-62,0	58,0-62,0	58,0-62,0
	s_2, мм	90,0-94,0	89,0-93,0	118,0-122,0	118,0-122,0
	d , мм	41,0-43,0	41,0-43,0	29,0-31,0	29,0-31,0
m_0	s_1, мм	58,0-62,0	58,0-62,0	58,0-62,0	58,0-62,0
	s_2, мм	63,0-67,0	58,0-62,0	58,0-62,0	58,0-62,0
	d , мм	41,0-43,0	41,0-43,0	29,0-31,0	29,0-31,0

Optimal areas of variation of geometric parameters are determined taking into account the technological features of heat recovery units.

4. Criteria of efficiency corresponding to the optimal values of the geometric parameters of the heat exchange surface of heat recovery units

Criterion efficiency	Hot water heat recovery unit		Air heating heat recovery unit	
	Chess bunch	Corridor bunch	Chess bunch	Corridor bunch
k	0,501	0,616	1,213	1,272
ε	0,309	0,321	0,332	0,335
m_0	1,891	1,948	3,557	3,694

The lower values of the exergy efficiency criteria correspond to the greater exergy efficiency of heat recovery units.

Discussion of research results. The values of the optimal ranges of variation of the parameters, which are the same when using all efficiency criteria, can be taken when designing heat recovery schemes. Such a parameter for heat recovery units with a staggered and in-line arrangement of pipes in a bundle is the area of variation of the distance s_1 between the panels in the direction transverse to the direction of the gas flow s_1 = 58.0-62.0 mm. The values of the areas of change in the diameter of pipes d = 41.0-43.0 mm for a water-tube heat exchanger with a corridor arrangement of pipes, as well as for an air-tube heat exchanger with a staggered and corridor arrangement of pipes d = 29.0-31.0 mm can also be used in the design of heat recovery schemes ... The use of the values of other parameters is carried out taking into account additional technological factors.

The exergy efficiency of hot water heat recovery units when using all efficiency criteria is higher than the exergy efficiency of air heating units. So for hot water heat recovery units, the k criterion is 2.0 times, the ε criterion is by 7.5%, the m0 criterion is 1.9 times lower than for air heating units. The thermal efficiency of heat recovery units correlates with their exergy efficiency. More efficient and compact hot water heat recovery units have advantages over air heating units in heat supply systems. When using schemes with hot water heat exchangers, the heat utilization factor of the furnace fuel increases, on average, by 20%. The feasibility of using air-heating heat recovery units is currently determined by the presence of additional technological factors. These are the need for a certain type of heat carrier, the cost of fuel, the possibility of using effective heating surfaces, the possibility of long-term operation of air-heating heat exchangers, stable heat load, etc. When using schemes using air-heating heat exchangers, the efficiency of the furnace increases, on average, by 12%.

For the first time, the optimal areas of variation of the geometric parameters of the heat exchange surface of hot-water and air-heating heat exchangers of glass-melting furnaces were established and an analysis of their efficiency was carried out. Recommendations have been developed on the possibility of using the results obtained when using heat recovery units in water heating schemes for heat supply systems and in combustion air heating schemes.

Conclusions and perspectives.

1. For the investigated heat recovery units, the levels of variation of the geometric parameters of the heat exchange surface are determined and the values of the efficiency criteria at the points of the central orthogonal compositional plan are calculated.
2. The regression equations are obtained, the optimal areas of variation of the parameters of the heat exchange surface of heat recovery units and the corresponding efficiency criteria are determined.

It has been established that heat recovery units with the following values of the areas of variation of the geometric parameters of the heat exchange surface can be used in heat recovery schemes for heating water in heat supply systems and for heating blast air:

- the values of the area of variation of the distance between the panels for heat exchangers with a staggered and corridor arrangement of pipes in a bundle s_1 = 58.0-62.0 mm.

- the values of the areas of change in the diameter of pipes for a hot water heat exchanger with a corridor arrangement of pipes d = 41.0-43.0 mm, for an air heating heat exchanger with a staggered and corridor arrangement of pipes d = 29.0-31.0 mm.

- the use of the values of the areas of change of other parameters is carried out taking into account additional technological factors.

It has been established that the exergy efficiency of water-heating heat recovery units when using all efficiency criteria is higher than the exergy efficiency of air-heating units. For hot water heat exchangers, the values of exergy criteria are lower than for air heating ones: k - 2.0 times, ε - 7.5%, m_0 - 1.9 times. The expediency of using the investigated heat recovery units in heat recovery circuits of glass melting furnaces is established, taking into account the results obtained and in the presence of certain technological factors.

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ОПТИМІЗАЦІЯ ГЕОМЕТРИЧНИХ ПАРАМЕТРІВ ТА АНАЛІЗ ЕКСЕРГЕТИЧНОЇ ЕФЕКТИВНОСТІ ТЕПЛОУТИЛІЗАТОРІВ СКЛОВАРНИХ ПЕЧЕЙ

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Анотація. *Наведено результати оптимізації геометричних параметрів поверхні теплообміну водо- і повітрогрійних теплоутилізаторів скловарних печей та аналіз їх ексергетичної ефективності. Забезпечення ефективної роботи теплоутилізаторів у різних теплових схемах є актуальною проблемою теплоенергетики.*

Метою роботи є встановлення оптимальних областей геометричних параметрів поверхні теплообміну теплоутилізаторів скловарних печей та аналіз їх ексергетичної ефективності. У роботі наводяться результати вирішення завдань, необхідних для досягнення поставленої мети:

- з використанням статистичних методів планування експерименту визначити для досліджуваних теплоутилізаторів рівні варіювання параметрів геометричної поверхні теплообміну та розрахувати значення критеріїв оцінки ефективності в точках центрального ортогонального композиційного плану;

- отримати рівняння регресії для досліджуваних теплоутилізаторів, визначити оптимальні області зміни геометричних параметрів теплообмінної поверхні і відповідні їм ексергетичні критерії ефективності.

Для визначення оптимальних областей геометричних параметрів поверхні теплообміну використовується комплексна методика на основі методів ексергетичного аналізу і статистичних методів теорії планування експерименту. Встановлено, що в теплоутилізаційних схемах для нагрівання води систем теплопостачання і для нагрівання дуттьового повітря можуть бути використані теплоутилізатори з такими значеннями областей зміни геометричних параметрів поверхні теплообміну:

- значення області зміни відстані між панелями для теплоутилізаторів при шаховому і коридорному розташуванні труб в пучку s_1 = 58,0-62,0 мм;

- значення областей зміни діаметра труб для водогрійного теплоутилизатора при коридорному розташуванні труб d = 41,0-43,0 мм і для повітрогрійного теплоутилизатора при шаховому і коридорному розташуванні труб d = 29,0-31,0мм;

- використання значень областей зміни інших параметрів здійснюється з урахуванням додаткових технологічних факторів.

Встановлено, що ексергетична ефективність водогрійних теплоутилізаторів у всіх випадках вище ексергетичної ефективності повітрогрійнних. Для водогрійних теплоутилізаторів значення ексергетичних критеріїв нижче, ніж для повітрогрійних: k – в 2,0 рази, ε – на 7,5 %, m_0 – в 1,9 рази. Встановлено доцільність застосування досліджуваних теплоутилізаторів в теплоутилізаційних схемах скловарних печей з урахуванням отриманих результатів і за наявності певних технологічних факторів.

Отримані результати та подальші розробки в області оптимізації режимних параметрів теплоутилізаторів скловарних печей дозволять забезпечити підвищення ефективності теплоутилізаційного обладнання для енергетичних установок.

Ключові слова: ***ексергетичні методи, планування експерименту, теплоутилизатор, оптимальні параметри***

ОПТИМИЗАЦИЯ ГЕОМЕТРИЧЕСКИХ ПАРАМЕТРОВ И АНАЛИЗ ЭКСЕРГЕТИЧЕСКОЙ ЭФФЕКТИВНОСТИ ТЕПЛОУТИЛИЗАТОРОВ СТЕКЛОВАРЕННЫХ ПЕЧЕЙ

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Аннотация. *Приведены результаты оптимизации геометрических параметров поверхности теплообмена водо- и воздухогрейных теплоутилизаторов стекловаренных печей и анализ их эксергетической эффективности. Обеспечение эффективной работы теплоутилизаторов в различных тепловых схемах является актуальной проблемой теплоэнергетики.*

Целью работы является установление оптимальных областей геометрических параметров поверхности теплообмена теплоутилизаторов стекловаренных печей и анализ их эксергетической эффективности. В работе приводятся результаты решения задач, необходимых для достижения поставленной цели:

- с использованием статистических методов планирования эксперимента определить для исследуемых теплоутилизаторов уровни варьирования параметров геометрической поверхности теплообмена и рассчитать значения критериев оценки эффективности в точках центрального ортогонального композиционного плана;

- получить уравнения регрессии для исследуемых теплоутилизаторов, определить оптимальные области изменения геометрических параметров теплообменной поверхности и соответствующие им эксергетические критерии эффективности.

Для определения оптимальных областей геометрических параметров поверхности теплообмена используется комплексная методика на основе методов эксергетического анализа и статистических методов теории планирования эксперимента. Установлено, что в теплоутилизационных схемах для нагрева воды систем теплоснабжения и для нагрева дутьевого воздуха могут быть использованы теплоутилизаторы со следующими значениями областей изменения геометрических параметров поверхности теплообмена:

- значения области изменения расстояния между панелями для теплоутилизаторов при шахматном и коридорном расположении труб в пучке s_1 = 58,0-62,0 мм;

- значения областей изменения диаметра труб для водогрейного теплоутилизатора при коридорном расположении труб d = 41,0-43,0 мм и для воздухогрейного теплоутилизатора при шахматном и коридорном расположении труб d = 29,0-31,0 мм;

- использование значений областей изменения других параметров осуществляется с учетом дополнительных технологических факторов.

Установлено, что эксергетическая эффективность водогрейных теплоутилизаторов во всех случаях выше эксергетической эффективности воздухогрейных. Для водогрейных теплоутилизаторов значения эксергетических критериев ниже, чем для воздухогрейных: k – в 2,0 раза, ε – на 7,5 %, m_0 – в 1,9 раза. Установлена целесообразность применения исследуемых теплоутилизаторов в теплоутилизационных схемах стекловаренных печей с учетом полученных результатов и при наличии определенных технологических факторов.

Полученные результаты и дальнейшие разработки в области оптимизации режимных параметров теплоутилизаторов стекловаренных печей позволят обеспечить повышение эффективности теплоутилизационного оборудования для энергетических установок.

Ключевые слова: ***эксергетические методы, планирование эксперимента, теплоутилизатор, оптимальные параметры***