This paper reports the results of studying the exergy effectiveness of thermal methods for anti-corrosion protection of the gas-draining tracts of boiler plants. These include the method of mixing heated air into flue gases, the method of passing part of the hot gases of the boiler through the bypass chimney, and a flue gas drying method. The research involved the devised comprehensive procedure based on an exergy approach. The dependences of exergy loss Elos and the heat- exergy criterion ε on the following parameters of thermal methods have been established: the amount of heated air N mixed into flue gases, the proportion of bypassed flue gases K, and the amount of dried flue gases R. A comparative analysis of the effectiveness of heat recovery systems when applying the methods considered has been performed. It has been established that for the method of mixing, E_{los} and ε at ambient temperature t_{en}=10 °C demonstrate the lowest values, that is, the efficiency of the system, in this case, is the highest. The most effective, when implementing the bypass method, is the heat recovery system at t_{en}=10 °C. Under the method of drying, at all values of the amount of dried flue gases, the loss of exergy is the lowest at t_{en}=0 °C. As regards the heat- exergy criterion, at values R≤20 %, the lowest values of ε are observed at t_{en}=10 °C. At R>20 %, the lowest values of ε are at t_{en}=0 °C. Thus, the efficiency of the system when implementing the method of drying is the highest at t_{en}=0 °C and at the amount of dried air of R>20 %. The study reported here would provide the necessary information for designing optimal heat recovery schemes. The development of this study is to establish the relationship between the exergy and environmental efficiency of thermal protection methods in order to further reduce toxic emissions

Keywords: heat recovery technologies, condensation prevention, exergy analysis methods, exergy efficiency criteria

COMPARATIVE ANALYSIS OF THE EXERGY EFFICIENCY OF METHODS FOR PROTECTING GAS EXHAUST DUCTS OF BOILER PLANTS

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1. Introduction

The rational use of fuel and energy resources is largely due to the improved efficiency of thermal power generating equipment and the increased service life of its operation. Fuel-consuming boilers in the communal thermal energy generation face a problem related to the operational reliability of gas drainage tracts when using modern heat recovery technologies involving deep cooling of exhaust gases. Implementing these technologies under some modes of operation of boiler plants leads to a decrease in the temperature of exhaust gases below their dew point and the condensation of part of the vapor contained in the flue gases. In this case, the thermal-moisture state of the exhaust gases corresponds to saturation conditions. When such gases enter the gas drainage channels, the residual moisture contained in the gases is condensed on the inner surfaces of the channels. Formed condensate causes corrosive destruction of gas-draining tracts due to its acidic reaction. The hydrogen condensate indicator for gaseous fuels is typically pH≤6. To prevent corrosion of gas-draining tracts, thermal methods are used to reduce the humidity of the exhaust gases. Analysis of the effectiveness of thermal methods for the anti-corrosion protection of gas drainage tracts implies systemic research using modern integrated approaches. A promising area that is increasingly employed in the energy sector is the application of exergy approaches to analyze the efficiency and optimize power plants. However, no studies have been carried out when investigating the issues related to the operation of gas exhaust ducts. Such studies could provide the necessary information for designing optimal heat recovery schemes. In addition, they would establish the relationship between the exergy and environmental efficiency of thermal methods of anti-corrosion protection of the boiler plant's gas exhaust ducts in order to further reduce toxic emissions into the atmosphere. Given the above, it is a relevant task to explore the exergy effectiveness of thermal methods of anti-corrosion protection of the gas exhaust ducts of boiler plants.

2. Literature review and problem statement

Papers [1, 2] report the results of studying thermal methods of protection of the gas exhaust ducts of boiler plants,

aimed at preventing condensation in them. However, many issues related to comprehensive research into thermal methods of protection of gas exhaust ducts, including studies of their exergy effectiveness, remained unresolved. The reason for this is the lack of a comprehensive procedure for assessing exergy efficiency of the thermal methods of protection of gas exhaust ducts.

The following works addressed the use of individual exergy characteristics to assess the exergy effectiveness of plants. Work [3] reported the analysis of exergy and energy performed for two configurations of heat recovery systems, which are used in small backup generators for electricity generation. Study [4] examines the results of a comparative exergy analysis of the gas engine's heat recovery systems for electricity generation. Several different approaches to the heat recovery of heat are proposed; their exergy efficiency has been compared. Work [5] compares various heat recovery units in terms of electricity generation and exergy loss in order to find the system with the highest exergy efficiency. Study [6] notes that exergy analysis reveals all aspects that affect the effectiveness of different types of systems and suggests the maximum number of possible improvements for the system under study. To analyze the efficiency of a boiler plant, work [7] used a balance method of exergy analysis, which examines the two main types of exergy losses associated with irreversible fuel combustion and heat transfer. The aim of paper [8] was to perform exergy and exergy-economic analysis for the elements of power plants whose effectiveness was assessed at different ambient temperatures.

However, in publications [3–10], the exergy efficiency of plants is estimated only by the values of their total exergy. Other studies use exergy efficiency to assess the exergy effectiveness of plants. Such approaches fail to reflect some important aspects of the examined processes. For example, when assessing the exergy effectiveness of plants with the specified characteristics, they do not take into consideration the purpose of the process, and there is ambiguity in the interpretation of useful effects and costs, as well as the impossibility to establish the localization of exergy losses.

Therefore, when assessing the effectiveness of power plants, it is advisable to use complex approaches that combine modern research methods and employ integrated criteria for efficiency evaluation, such as exergy-technological, thermal- exergy, etc. This approach was applied in work [9] to optimize the parameters for a contact plate air heater, which is part of the combined heat recovery system of a boiler plant, designed to heat water and blow air. However, that approach was not used to investigate the exergy effectiveness of thermal methods for protecting gas exhaust ducts of boiler plants due to the lack of an appropriate comprehensive methodology.

All this suggests that it is appropriate to conduct research on analyzing the exergy effectiveness of thermal methods of anti-corrosion protection of gas exhaust ducts of boiler plants involving a comprehensive procedure that includes the structural-variant and balance methods of exergy analysis, as well as appropriate criteria for evaluating effectiveness. Such a study would provide the necessary information for designing optimal heat recovery schemes. In addition, they would establish the relationship between the exergy and environmental efficiency of thermal methods of anti-corrosion protection of the gas exhaust ducts of boiler plants in order to further reduce toxic emissions into the atmosphere.

3. The aim and objectives of the study

The aim of this study is to analyze the exergy effectiveness of thermal methods of anti-corrosion protection of gas exhaust ducts when changing the governing parameters of thermal methods of protection, as well as define those parameters at which the efficiency of thermal methods is maximal. This would provide the necessary information for designing optimal heat recovery schemes based on the thermal methods of protection of gas exhaust ducts.

To accomplish the aim, the following tasks have been set:
– to develop structural schemes of the main elements of heat recovery systems based on different thermal protection methods as part of the devised comprehensive methodology for assessing the exergy effectiveness of thermal methods of protection of gas exhaust ducts;
– to select exergy characteristics to assess the exergy effectiveness of thermal protection methods;
– to devise a general system of exergy and material balance equations to calculate the exergy characteristics of heat recovery systems based on different thermal protection methods;
– to derive dependences of the exergy characteristics of heat recovery systems on the governing parameters of thermal methods of protection of gas exhaust ducts: the amount of heated air mixed in flue gases, the proportion of bypassed flue gases, and the amount of dried flue gases.

4. The study materials and methods

The following thermal methods of anti-corrosion protection of the gas exhaust ducts of boiler plants were to be considered. A first thermal method of protection (air-based) is to mix part of the heated air in flue gases after a heat recovery unit. When using this method, the temperature of the mixture of flue gases and air increases, the relative and absolute humidity of the gases decrease, and their dew point decreases. A second method (when part of the exhaust gases of the boiler bypasses the heat recovery unit) is aimed only at reducing the relative humidity of the mixture of exhaust gases by increasing their temperature. A third method (the drying of gases in the gas heater) essentially implies increasing the temperature and reducing the relative humidity of the flue gases cooled in the heat recovery unit by heating them in the surface heat exchanger (gas heater), installed after the heat recovery unit.

We have considered gas-fueled plants equipped with a boiler, whose heat capacity is 2 MW, and heat recovery units for heating water. The boiler's operation modes corresponded to the heat-grid schedule of a boiler plant with a temperature difference of Δt=115–70 °C. When the heat load of the boiler plant was reduced below 50 %, the number of working boilers decreased with a corresponding increase in their thermal capacity. The temperature of the exhaust flue gases after the boiler under a rated mode was 166 °C. The initial temperature of mixed air was taken equal to 250 °C.

To analyze the exergy effectiveness of thermal methods of anti-corrosion protection of the gas exhaust ducts of boiler plants, a comprehensive procedure based on the exergy analysis methods has been devised. A given procedure includes the following steps:

– exergy analysis based on the structural and variant methods;

– the construction of a general system of exergy balance equations;

– the selection of exergy criteria to assess the effectiveness of thermal methods.

The structural-variant methods of exergy analysis make it possible to identify the main elements of heat recovery systems, for which a change in exergy efficiency most significantly affects the change in the efficiency of the system in general. These methods allow the development of structural schemes for these elements, which are used to build balance equations based on a general system of the exergy and material balance equations. The resulting balance equations are applied to calculate exergy characteristics. Appropriate calculations have been carried out, as well as structural schemes have been designed, for the examined heat recovery schemes based on the thermal protection methods involving the identification of exergy flows between elements of the structure.

In the procedures that use integrated balance analysis methods, thermodynamic balances are recorded in a certain form, for example, in the form of exergy, energy, matrix balances. These procedures are effective due to the small number of parameters required for calculation, the simplicity of estimation and analytical methods for deriving the exergy characteristics, as well as the high accuracy of results (0.3–0.5 %). For the examined heat recovery systems based on thermal protection methods, a general system of exergy balance equations has been built, on the basis of which the equations of exergy balance were constructed in accordance with the structural schemes. These equations are used to calculate the exergy characteristics needed to analyze the exergy effectiveness of thermal methods of protecting gas exhaust ducts.

The exergy criteria for assessing the effectiveness of thermal methods of anti-corrosion protection of gas exhaust ducts are selected taking into consideration the degree of sensitivity of the criteria to a change both in the regime and structural parameters of heat recovery systems. This paper has considered the quantity of exergy losses E_{los} used in various studies, and the integrated efficiency assessment criteria proposed by us earlier, which make it possible to assess the effectiveness of a heat recovery system from the thermodynamic, thermal-technical, and technological perspectives. These include a thermal-exergy criterion of efficiency $\varepsilon=E/Q$, an exergy-technological criterion $k_\text{т}=Em/Q^2$, a technological criterion $m_0=m/Q$, an exergy criterion $k_\text{т}=\eta_{ex}/\eta_{ex}^{id}$. We have selected the criteria for evaluating the examined heat recovery schemes based on thermal protection methods by taking into consideration the degree of sensitivity of the criteria to a change both in the regime and structural parameters of heat recovery systems. To this end, a factor k_s has been proposed, which determines the relative changes in the examined performance criteria when the relevant parameters are changed. Those are the geometric parameters of the heat-exchange surface of a heat recovery unit, which is part of the heat recovery schemes, and the regime parameters, such as the initial temperature of flue gases, water temperature, etc.

When establishing the dependences of exergy characteristics on the parameters of thermal methods, each series of experiments implied their randomized sequence. The variance uniformity was assessed according to the Cochran criterion. The Fischer criterion was employed to check the adequacy of the results to data used.

5. Results of studying the exergy effectiveness of thermal methods of protection of gas exhaust ducts of boiler plants

5. 1. Structural schemes of the main elements of heat recovery systems based on different thermal methods of protection of gas exhaust ducts

We have performed a study that involved the structural-variant methods of exergy analysis, which have allowed us to identify the basic elements of heat recovery systems based on different methods of protection of gas exhaust ducts. For these elements, a change in exergy efficiency exerts the most significant impact on the change in the efficiency of the system. Based on our study, appropriate structural schemes have been designed (Fig. 1–3).
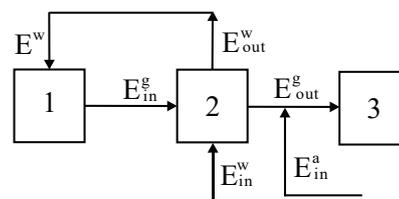

Fig. 1. Structural scheme of the main elements in a heat recovery system based on the method of mixing a part of the heated air into flue gases after the heat recovery unit: 1 — boiler; 2 — heat recovery unit; 3 — chimney
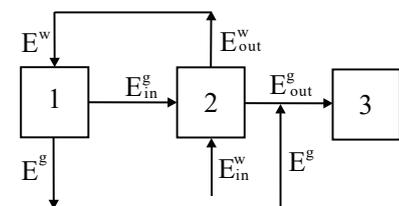

Fig. 2. Structural scheme of the main elements in a heat recovery system based on the method for bypassing flue gases: 1 — boiler; 2 — heat recovery unit; 3 — chimney
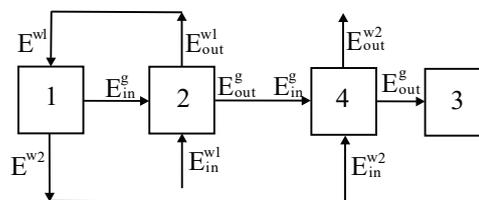

Fig. 3. Structural scheme of the main elements in a heat recovery system based on the method of drying the flue gases, cooled in the heat recovery unit, in the gas heater: 1 — boiler; 2 — heat recovery unit; 3 — chimney; 4 — gas heater

Here: E – exergy. Upper indices: g, a, w – flue gases, air, water. Bottom indices: in, out – inlet, outlet.

The designed structural schemes, shown in Fig. 1–3, reflect the identification of exergy flows among the main elements of heat recovery systems based on various thermal methods of anti-corrosion protection of gas exhaust ducts. For each thermal method, these structural schemes are used for the construction of balance equations based on the devised general system of exergy and material balance equations.

5. 2. Choosing exergy characteristics to assess the exergy effectiveness of thermal methods

The criteria for assessing the efficiency of power plants have different sensitivities to changing their regime and structural parameters. We selected the criteria for the effectiveness of boiler plants with the examined heat recovery systems based on thermal protection methods using the medium degree of sensitivity of the criteria to a change both in their regime and structural parameters. The following criteria were investigated: exergy losses E_{los}, thermal-exergy efficiency criterion $\varepsilon=E/Q$, exergy-technological criterion $k_\text{т}=Em/Q^2$, technological criterion $m_0=m/Q$, exergy criterion $k_m=\eta_{ex}/\eta_{ex}^{id}$.

The mean sensitivity of the criteria to changes in both the regime and structural parameters of heat recovery systems was determined by the proposed factor k_s. The k_s factor determines the relative changes in the efficiency criteria under consideration when changing the geometric parameters of the heat-exchange surface of a heat recovery unit: the height of the edge, the thickness of the edge, and the step of edging, as well as the mode parameters such as the initial temperature of the flue gases, the temperature of the water, etc. Table 1 gives the results of our calculations of the mean sensitivity of the efficiency criteria to a change in both the regime and structural parameters of heat recovery systems.

Table 1

Mean sensitivity of efficiency criteria to changes in the regime and structural parameters of heat recovery systems

Efficiency criterion	E_{los}, kW	ε	k_m, kW/kg	m_0, kg/kW	k_{ex}
k_s	1.35	1.40	1.20	0.20	1.25

As one can see from Table 1, the exergy loss of E_{los} and the thermal-exergy efficiency criterion ε are most sensitive to changes in both the regime and structural parameters of heat recovery systems. These exergy criteria are used in this work to study the exergy effectiveness of heat recovery systems based on various thermal methods of anti-corrosion protection.

5. 3. The system of exergy and material balance equations to calculate the exergy characteristics of heat recovery systems

In accordance with the main stages in the devised methodology, a general system of exergy and material balance equations has been built for heat recovery systems with different heat carriers:

$$\sum_{i=1}^{n}\Delta E_i + E_{los} = 0,$$

$$\sum_{i=1}^{n}G_{i\,in}h_{i\,in} - \sum_{i=1}^{n}G_{i\,out}h_{i\,out} = 0,$$

$$\sum_{i=1}^{n}G_{iin} - \sum_{i=1}^{n}G_{iout} = 0,$$

$$\Delta E^w = G^w\left(h_{out}^w - T_{en}s_{out}^w\right) - G^w\left(h_{in}^w - T_{en}s_{in}^w\right),$$

$$\Delta E^g =$$

$$=G^g\begin{bmatrix}c_{pdr}^g\left(T_{in}^g-T_{out}^g\right)-\\[4pt]-T_{en}\begin{pmatrix}c_{pdr}^g\ln\dfrac{T_{in}^g}{T_{out}^g}-\\[4pt]-\dfrac{R}{\text{М}_{dr}^g}\ln\dfrac{p_{in}^g-p_p^{st}\left(T_{in}\right)}{p_{out}^g-p_p^{st}\left(T_{out}\right)}\end{pmatrix}\end{bmatrix}+$$

$$+G^g d_{in}\begin{bmatrix}c_{pdr}^{st}\left(T_{in}^{st}-T_{en}\right)-\\[4pt]-T_{en}\begin{pmatrix}c_{pdr}^{st}\ln\dfrac{T_{in}^{st}}{T_{en}}-\\[4pt]-\dfrac{R}{\text{М}_{dr}^{st}}\ln\dfrac{p_p^{st}\left(T_{in}\right)}{\varphi_{en}p_{en}^{sat}}\end{pmatrix}\end{bmatrix}-$$

$$-G^g d_{out}\begin{bmatrix}c_{pdr}^{st}\left(T_{out}^{st}-T_{en}\right)-\\[4pt]-T_{en}\begin{pmatrix}c_{pdr}^{st}\ln\dfrac{T_{in}^{st}}{T_{en}}-\\[4pt]-\dfrac{R}{\text{М}_{dr}^{st}}\ln\dfrac{p_p^{st}\left(T_{out}\right)}{\varphi_{en}p_{en}^{sat}}\end{pmatrix}\end{bmatrix},$$

$$\Delta E^g = G^g c_p^g\left(T_{in}^g-T_{out}^g\right)-$$
$$-G^g T_{pn}c^g\ln\left(T_{in}^g/T_{out}^g\right)-$$
$$-\left(G^g T_{en}R/\text{М}^g\right)\ln\left(p_{in}^g/p_{out}^g\right),$$

$$\Delta E^a = G^a c_p^a\left(T_{in}^a-T_{out}^a\right)-$$
$$-G^a T_{pn}c^a\ln\left(T_{in}^a/T_{out}^a\right)-$$
$$-\left(G^a T_{en}R/\text{М}^a\right)\ln\left(p_{in}^a/p_{out}^a\right).$$

Here:
– c_p – specific heat capacity;
– d – moisture content;
– E – exergy;
– G – heat carrier flow rate;
– h – enthalpy;
– m – mass;
– n – the number of heat carriers in a system;
– p – pressure;
– R– universal gas constant;
– Q – thermal productivity;
– s – entropy;
– T – absolute temperature;
–μ – molecular mass;
–φ_{en} – relative humidity of the environment.
Upper indices: g, st, a, w – flue gases, vapor, air, water.
Bottom indices: en – environment: in, out – inlet, outlet; dr – dry; i – ideal; los – losses; p – partial; sat – saturated.
The balance equation system contains an equation to change the exergy of flue gases, which takes into consideration their moisture content at the inlet and outlet of the heat recovery unit.

5. 4. Dependences of the exergy characteristics of heat recovery systems on the regime parameters of boilers

The structural schemes of heat recovery systems and the system of balance equations were used to determine

the exergy losses E_{los} and the heat-exergy criterion ε of the efficiency of heat recovery systems based on various thermal methods of anti-corrosion protection. The calculations were carried out at different parameters of thermal methods. These include is the amount of heated air N mixed into the flue gases, the amount of bypassed flue gases K, and the amount of dried flue gases R (Tables 2–4).

Table 2

Results of the calculation of exergy characteristics for the air method

t_{en}, °C	N, %	ΔE^w, kW	ΔE^g, kW	E_{los}, kW	ε
−10	0	7.07	19.98	12.92	0.210
	4	7.07	18.42	11.35	0.182
	8	7.07	16.93	9.86	0.159
	12	7.07	15.5	8.43	0.136
	16	7.07	14.10	7.03	0.113
0	0	7.42	24.7	17.28	0.202
	4	7.42	23.10	15.68	0.184
	8	7.42	21.60	14.18	0.167
	12	7.42	20.10	12.68	0.148
	16	7.42	18.60	11.18	0.131
10	0	4.95	13.80	8.85	0.098
	4	4.95	13.00	8.05	0.089
	8	4.95	12.10	7.15	0.079
	12	4.95	11.22	6.28	0.069
	16	4.95	10.33	5.38	0.059

Here, t_{en} is the temperature of the environment. Upper indices: $w1$, $w2$ – heated, cooled water.

Based on the results of the calculation of exergy characteristics, the dependences of the exergy losses E_{los} and the heat-exergy efficiency criterion ε on the regime parameters of heat recovery systems for three thermal methods of anti-corrosion protection (Fig. 4–6) have been established.

Table 3

Results of the calculation of exergy characteristics for the bypass method

t_{en}, °C	K, %	ΔE^w, kW	ΔE^g, kW	E_{los}, kW	ε
−10	0	8.11	16.00	7.89	0.127
	10	7.56	15.16	7.60	0.134
	20	6.47	13.97	7.50	0.147
	30	5.92	12.76	6.84	0.151
	40	5.38	11.41	6.03	0.153
0	0	7.27	21.13	13.86	0.162
	10	6.85	20.10	13.25	0.169
	20	6.03	18.73	12.70	0.180
	30	5.21	17.24	12.03	0.192
	40	4.80	15.71	10.91	0.197
10	0	4.83	20.02	15.20	0.168
	10	4.59	19.53	14.95	0.174
	20	4.34	18.86	14.52	0.179
	30	4.10	17.97	13.87	0.184
	40	3.86	16.86	13.00	0.187

Table 4

Results of the calculation of exergy characteristics for the method of drying

t_{en}, °C	R, %	ΔE^{w1}, kW	ΔE^{w2}, kW	ΔE^g, kW	E_{los}, kW	ε
−10	0	7.07	0.30	23.90	17.13	0.275
	10	7.07	0.30	21.64	14.87	0.239
	20	7.07	0.30	19.20	12.43	0.200
	30	7.07	0.30	16.60	9.83	0.159
	40	7.07	0.30	13.83	7.06	0.114
	50	7.07	0.30	10.78	4.01	0.064
	60	7.07	0.30	7.67	0.90	0.014
0	0	7.42	0.07	29.43	22.08	0.259
	10	7.42	0.07	27.32	19.97	0.234
	20	7.42	0.07	24.88	17.53	0.205
	30	7.42	0.07	22.27	14.92	0.175
	40	7.42	0.07	19.78	12.43	0.146
	50	7.42	0.07	16.41	9.06	0.106
	60	7.42	0.07	13.21	5.86	0.070
10	0	4.95	0.09	24.44	19.58	0.216
	10	4.95	0.09	23.37	18.51	0.204
	20	4.95	0.09	22.13	17.27	0.190
	30	4.95	0.09	20.91	16.05	0.177
	40	4.95	0.09	19.32	14.42	0.159
	50	4.95	0.09	17.66	12.71	0.140
	60	4.95	0.09	15.72	10.86	0.119

Smaller values of exergy losses and heat-exergy efficiency criterion in Fig. 4, 5 correspond to the greater exergy efficiency of heat recovery systems based on different thermal methods of anticorrosion protection of the gas exhaust ducts of boiler plants. The adequacy of the results used was determined by the Fisher criterion F. The Fischer criterion estimation value, which is, on average, $F_c=0.88$, was compared with the tabular value $F_t=2.34$ found for the number with a degree of freedom $f_1=30$ and $f_2=7$. Because $F_c<F_t$, our results are adequate to the data used.
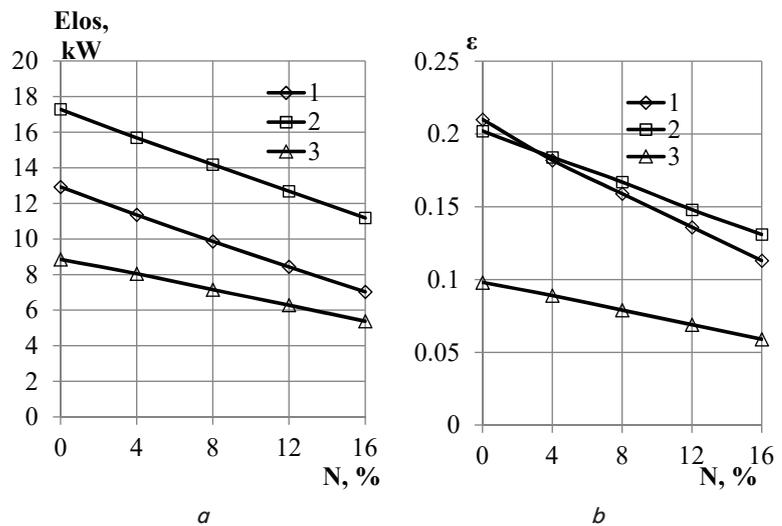

Fig. 4. Dependence of exergy characteristics on the amount of heated air N mixed into flue gases for the mixing method: a – dependence of exergy losses E_{los} on N; b – dependence of the heat-exergy criterion of efficiency ε on N; $1 - t_{en}=-10$ °C; $2 - t_{en}=0$ °C; $3 - t_{en}=10$ °C;
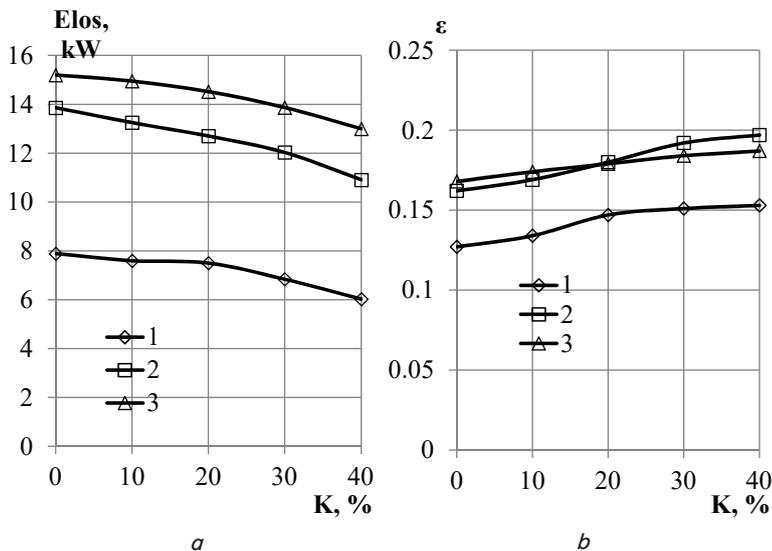
Fig. 5. Dependence of exergy characteristics on the amount of bypassed flue gases K for the method of bypassing: a – dependence of exergy losses E_{los} on K; b – dependence of the heat-energy criterion of efficiency ε on K; 1 – t_{en}=−10 °C; 2 – t_{en}=0 °C; 3 – t_{en}=10 °C
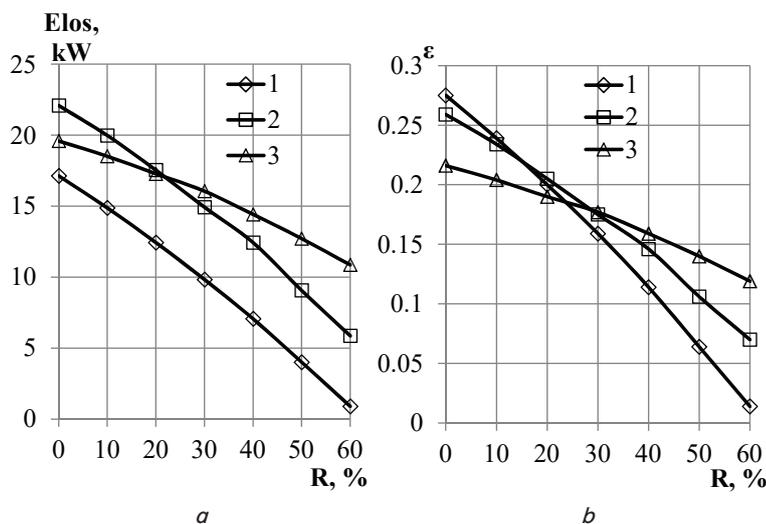

Fig. 6. Dependence of exergy characteristics on the amount of dried flue gases R for the method of drying: a – dependence of exergy losses E_{los} on R; b – dependence of the heat-energy criterion of efficiency ε on R; 1 – t_{en}=−10 °C; 2 – t_{en}=0 °C: 3 – t_{en}=10 °C

6. Discussion of results of studying the exergy effectiveness of thermal methods of protection of gas exhaust ducts

6. 1. Analysis of changes in the exergy characteristics of heat recovery systems based on thermal protection methods

To study the exergy efficiency of energy plants, only exergy efficiency is mostly used. This approach does not reflect some important aspects of the processes under study. For example, this does not take into consideration the purpose of the process, there is ambiguity in the interpretation of useful effects and costs, and the impossibility to localize exergy losses. In this paper, a comprehensive procedure, which includes the structural-variant methods, the integrated balance methods of exergy analysis, and the selection of exergy characteristics to evaluate exergy efficiency, has been used for the first time to analyze the exergy effectiveness of thermal protection methods. According to the data acquired, the difference in the temperature of heat carriers at the inlet and outlet of heat recovery units, the temperature level and flow rate of heat carriers, as well as the water content of flue gases, have a significant impact on the exergy characteristics of heat recovery systems. The nature and degree of influence of these parameters varies and depends on the mode of operation of the boiler in accordance with its heat load depending on the ambient temperature t_{en}.

With the reduction of the heat load on the boiler, there is a general tendency to increase exergy losses due to lower temperature of exhaust gases from the boiler, the increased consumption of gases, as well as a decrease in the temperature of the water heated in the heat recovery unit. However, at an ambient temperature of about 0 °C, the examined heat grid schedule of a boiler plant implies switching the boilers to the rated mode of operation due to a decrease in the total number of boilers working. At this temperature, the general trend is disrupted; for different thermal methods, the impact of this transition is different.

It is advisable to analyze consistently the exergy characteristics of heat recovery systems based on various thermal methods of anti-corrosion protection of gas exhaust ducts.

When implementing the air method at one ambient temperature, the magnitude of change in the exergy of water remains constant, and the loss of exergy and the change in the heat-exergy criterion depend on the magnitude of the change in the exergy of flue gases (Table 2). As a result of mixing part of the heated air in flue gases after the heat recovery unit (Fig. 1), there is an increase in the temperature of the mixture of flue gases and air, an increase in the flow of the mixture, and a decrease in its moisture content at the heat recovery unit outlet. The increase in the temperature of the mixture reduces the magnitude of change in the exergy of flue gases, and the increase in the consumption of the mixture and the decrease in moisture content increases the magnitude of change in the exergy of flue gases all other things being equal. The combined impact of these parameters leads to the following results.

When the amount of air mixed increases for all ambient temperature values the loss of exergy and the value of a heat-exergy criterion decrease. At ambient temperature t_{en}=10 °C, these exergy characteristics accept the lowest values (Fig. 4).

When implementing the bypass method for ambient temperatures t_{en}=10 °C and t_{en}=0 °C the magnitude of changes in the exergy of flue gases, as well as the loss of exergy, is about the same as in the case of mixing method (Table 3). Namely, when the amount of bypassed flue gases increases, the loss of exergy decreases (Table 3, Fig. 5, a). However,

the magnitudes of the heat-energy criterion increase as the amount of bypassed flue gases increases due to the reduction in the thermal power of a heat recovery system (Fig. 5, *b*). For ambient temperature t_{en}=10 °C, the resulting water content of the flue gases begins to have a more significant effect on the magnitude of the change in the exergy of the flue gases. As a result, the loss of exergy is higher compared to that at ambient temperatures t_{en}=10 °C and t_{en}=0 °C.

When implementing the method of drying, similar to the case of the air method, at the same ambient temperature, the amount of change in the water exergy remains constant (Table 4). The loss of exergy and the change in the heat-exergy criterion depend on the magnitude of the change in the exergy of flue gases. For all ambient temperature values, when the amount of dried gases increases, the values of exergy loss and heat-exergy criterion are reduced (Table 4, Fig. 6). At the same time, the degree of a decrease in the exergy characteristics is different for different ambient temperature values. The highest reduction is at ambient temperature t_{en}=10 °C, the lowest – at t_{en}=10 °C (Fig. 6). At t_{en}=0 °C, compared to t_{en}=10 °C, there is an increase in the loss of exergy due to an increase in the difference in the incoming and outgoing temperature of flue gases, an increase in temperature levels, and an increase in the consumption of flue gases. However, at t_{en}=10 °C, the decrease in temperature has a slightly greater effect on the amount of exergy loss than other parameters, and the loss of exergy may decrease (Fig. 6, *a*). At all values of the amount of dried flue gases R, the loss of exergy is the lowest at the ambient temperature of t_{en}=0 °C (Fig. 6, *a*). As regards the heat-exergy criterion, for $R \leq 20$ %, the lowest efficiency criterion values are observed at ambient temperature t_{en}=10 °C. At $R > 20$ %, the lowest efficiency criteria values are at ambient temperature t_{en}=0 °C (Fig. 6, *b*).

Our results show that heat recovery systems based on different thermal methods of anti-corrosion protection of gas exhaust ducts are characterized by rather close indicators of exergy characteristics. Further differentiation of the thermal methods considered should be subsequently performed by establishing the relationship between the exergy and environmental characteristics.

6. 2. Determining parameters values at which the effectiveness of thermal anti-corrosion protection methods is maximal

When implementing the method of mixing, the loss of exergy and the value of the heat-exergy criterion at ambient temperature t_{en}=10 °C accept the lowest values, that is, the efficiency of the system, in this case, is the highest (Fig. 4). The heat recovery system has the greatest efficiency when implementing the bypassing method at ambient temperature t_{en}=10 °C (Fig. 5). For the method of drying, at all values of the amount of dried air, the loss of exergy is the lowest at ambient temperature t_{en}=0 °C (Fig. 6, *a*). As regards the heat-exergy criterion, for $R \leq 20$ %, the lowest efficiency criterion value is observed at ambient temperature t_{en}=10 °C. At R>20 %, the lowest efficiency criteria value is at ambient temperature t_{en}=0 °C (Fig. 6, *b*). Thus, the efficiency of the system when implementing the method of drying is the highest at t_{en}=0 °C at the amount dried flue gases air $R > 20$ %.

The comparative analysis of the exergy effectiveness of the examined thermal methods of protection of gas exhaust ducts reveals that heat recovery systems based on different thermal protection methods are characterized by fairly close indicators of exergy characteristics. Greater differentiation of the considered thermal methods of anti-corrosion protection of the gas exhaust ducts of boiler plants can be achieved by establishing a relationship between the exergy and environmental efficiency of thermal methods.

Further development of our study is to follow the specified direction in order to further reduce toxic emissions into the atmosphere.

7. Conclusions

1. As part of the developed comprehensive procedure for analyzing exergy efficiency, we have designed the structural schemes of the main elements of heat recovery systems based on the thermal methods of anti-corrosion protection of gas exhaust ducts. The schemes identify exergy flows among the elements of the structure. Our schemes make it possible, based on a general system of exergy and material balance equations, to construct balance equations to calculate the exergy characteristics needed to assess the effectiveness of thermal methods of protection of gas exhaust ducts.

2. To study the exergy effectiveness of thermal methods of protection of gas exhaust ducts, we have proposed the parameters of the amount of exergy losses E_{los} and the heat-energy efficiency criterion ε as criteria for evaluation. These criteria have the greatest degree of sensitivity to changes in both the regime and structural parameters of heat recovery systems.

3. A general system of exergy and material balance equations has been built. The equation system includes an equation to change the exergy of flue gases, taking into consideration their moisture content at the inlet and outlet of the heat recovery unit. Using a general system of balance equations, the exergy characteristics of heat recovery systems based on different thermal protection methods have been calculated, taking into consideration the designed structural schemes.

4. We have derived the dependences of exergy losses E_{los} and heat-energy efficiency criterion ε on the governing parameters of thermal methods of protection of gas exhaust ducts: the amount of heated air N mixed in flue gases, the proportion of bypassed flue gases K, and the amount of dried flue gases R. The adequacy of our results to the data used was determined by the Fisher F criterion. It was established:

– when implementing the method of mixing, the loss of exergy and the value of the heat-exergy criterion at ambient temperature t_{en}=10 °C accept the lowest values, that is, the efficiency of the system, in this case, is the highest;

– the heat recovery system demonstrates the greatest efficiency when implementing the bypassing method at ambient temperature t_{en}=10 °C;

– under the method of drying, at all values of the amount of dried flue gases, the loss of exergy is the lowest at ambient temperature t_{en}=0 °C. As regards the heat-exergy criterion, for the values of $R \leq 20$ %, the lowest efficiency criteria values are observed at ambient temperature t_{en}=10 °C. At $R > 20$ %, the lowest efficiency criteria values are at ambient temperature t_{en}=0 °C. Thus, the efficiency of the system when implementing the method of drying is the highest at t_{en}=0 °C and at the amount of dried flue gases of $R > 20$ %.

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