Для пластинчастого повітронагрівача, що входить в теплоутилізаційну систему котельної установки, досліджено вплив його теплофізичних параметрів на втрату ексергетичної потужності при різних режимах роботи опалювального котла. Методика розрахунку втрат у даному повітронагрівачі ґрунтується на використанні комплексного підходу, який поєднує ексергетичні методи з методами термодинаміки незворотних процесів. Математична модель включає диференційне рівняння балансу ексергії та рівняння теплопровідності для повітронагрівача при граничних умовах третього роду. Диференційне рівняння балансу ексергії розв'язано сумісно з рівнянням теплопровідності. В результаті розв'язання отримано розрахункові залежності для визначення втрат ексергетичної потужності, пов'язаних з процесами теплопередачі.

Розраховано втрати ексергетичної потужності в досліджуваних теплоутилізаторах при зміні коефіцієнта теплопровідності пластини, коефіцієнта тепловіддачі з боку димових газів і режиму роботи котла. Отримані залежності від коефіцієнта теплопровідності для розглянутих режимів роботи котла мають дві чітко виражені ділянки, на першій з яких спостерігається відносно невелике збільшення втрат ексергетичної потужності при зменшенні коефіцієнта теплопровідності, на другій – втрати ексергетичної потужності в теплоутилізаторі порівняно різко зростають. Для дослідженої послідовності режимів котла перехід від його максимальної теплопродуктивності до мінімальної супроводжується зменшенням втрат ексергетичної потужності. Аналогічний характер має також залежність від коефіцієнта теплопровідності відносного вкладу втрат ексергетичної потужності в процесах теплопередачі в їх сумарні значення в теплоутилізаторі. При цьому мають місце незначні відмінності відносного вкладу даних втрат при різних режимах роботи котла. Коефіцієнт тепловіддачі з боку димових газів в межах одного режиму котла менш суттєво, ніж коефіцієнт теплопровідності матеріалу теплообмінної поверхні, впливає на втрати ексергетичної потужності в процесах теплопередачі. Встановлено області зміни коефіцієнта теплопровідності та режими роботи котла, за яких втрати ексергетичної потужності в теплоутилізаторі мінімальні

Ключові слова: втрати ексергетичної потужності, теплофізичні параметри, процеси теплопередачі, режими роботи котла

UDC 621.036.7
DOI: 10.15587/1729-4061.2018.147526

EFFICIENCY OF THE AIR HEATER IN A HEAT RECOVERY SYSTEM AT DIFFERENT THERMOPHYSICAL PARAMETERS AND OPERATIONAL MODES OF THE BOILER

N. Fialko
Doctor of Technical Sciences, Professor, Honored Worker of Scientist of Ukraine, Corresponding Member of the National Academy of Science of Ukraine, Head of Department*
E-mail: nmfialko@ukr.net

A. Stepanova
PhD, Leading Researcher*
E-mail: A.I.Stepanova@nas.gov.ua

R. Navrodska
PhD, Senior Researcher, Leading Researcher*
E-mail: navrodska-ittf@ukr.net

N. Meranova
PhD, Senior Researcher, Leading Researcher*
E-mail: mnata1956@ukr.net

J. Sherenkovskii
PhD, Senior Researcher, Leading Researcher*
E-mail: j_sher@ukr.net

*Department of Thermophysics of Energy Efficient Heat Technologies
Institute of Engineering Thermophysics of NAS of Ukraine
Zhelyabova str., 2a, Kyiv, Ukraine, 03057

1. Introduction

One of the important factors for saving fuel and material resources in energy generation is to utilize the heat of waste gases from heat power units. Implementation of effective heat utilization technologies makes it possible to significantly improve the utilization ratio of heat from fuel of these units. At present, studies into the efficiency and optimization of heat recovery systems are typically conducted using any single method of analysis – exergetic, technological, etc. However, that does not make it possible to analyze the work of units from different standpoints and to employ, in the development of its designs, parameters that are maximally close to optimal. Forming the specified technologies must be based on the application of modern integrated approaches to the analysis of effectiveness of heat recovery equipment. A series of studies address the operation of energy converting systems based on the comprehensive methods of exergetic economy, the methods that combine exergy analysis with elements from the theory of linear systems, multilevel optimization, etc. As far as modern heat recovery systems are concerned, the analysis is complicated by the need to take into consideration the large number of structural, technological and thermal-technical parameters that are responsible for the effectiveness of such systems.

The proposed integrated approach to the analysis of effectiveness of heat recovery equipment based on exergetic methods, as well as methods of thermodynamics of irreversible processes, allows us to overcome the identified difficulties. In this case, a dependence of the performance characteristics of this equipment on the specified defining parameters could be obtained in an analytical form. Given the above, it is a relevant task to analyze the effectiveness of heat recovery systems using integrated approaches.

2. Literature review and problem statement

Exergy analysis is known to be an important tool to study the effectiveness of energy plants of different types. This is related, particularly, to that some exergetic characteristics are quite sensitive to changes in the structural and operating parameters of plants and could be used as a measure of their thermodynamic efficiency. Paper [1] noted that the exergy analysis could be regarded as a technique to acquire information that identifies areas in which technical and other improvements could be implemented when developing energy technologies.

Papers [2–4] provide an example of research based on the class of exergetic methods. In [2], an installation for the production of hydrogen from biomass was used as an example of using exergy analysis to assess both its overall and exergetic efficiency. Paper [3] reported an exergy analysis for the efficiency of an absorption refrigerating machine, and defined the variables that unambiguously characterize its performance. To analyze the efficiency of a boiler room, article [4] applied a balance method of exergetic analysis, which is used to consider two basic types of exergetic losses associated with irreversible combustion of fuel and a heat transfer. However, applying a given method to the installation as a whole does not make it possible to analyze the effectiveness of each of its element, to localize exergetic losses and to determine values for characteristics at which these losses are minimal.

Paper [5] noted that even though exergy analysis is a powerful tool to design, evaluate, and improve energy conversion systems, the lack of an appropriate formal procedure to employ the results of a given analysis significantly limits the scope of its application. Analyzing the effectiveness of the specified units using the methods of exergy analysis only, without the application of integrated approaches, does not make it possible to examine work of these units in terms of technological, thermophysical, economic, and other aspects, which limits the completeness of the analysis performed. Studies [6–9] are the examples of research based on the employment of integrated approaches.

Based on an integrated exergetic-economic approach, the authors of [6] assessed the operation of a combined cycle power plant. They considered total exergetic losses, as well as losses for each component of the system, which are determined by the physical, technological, and economic constraints. The authors analyzed the level of eliminated exergetic losses, which provides a realistic assessment of the potential for improving the thermodynamic efficiency of the system's components.

The authors of paper [7], using an integrated approach based on the combination of a method of exergetic analysis and a multilevel optimization method, acquired data on the optimal values for the regime and structural parameters of a combined heat recovery installation that exploited water- and air heating equipment. Applying the results of the conducted research when designing the installation helped improve its effectiveness by 2.5 %.

Study [8] reports a comparative analysis of two comprehensive methods to optimize a heat recovery plant for boiler rooms, which combine, in the first case, the exergetic and structurally-variant methods, in the second case, the exergetic method and a method of multilevel optimization. According to the results of comparison, it has been shown that the exergetic-technological efficiency of a heat recovery plant, optimized by using a multilevel optimization method, is 2 % higher than that of the same installation, optimized by applying a structural-variant method.

Paper [9] outlines basic thermodynamic provisions for the integrated approach to analyzing the effectiveness and optimization of heat recovery systems based on the use of exergetic and structural-variant methods, adapted to studying heat recovery systems with complex structures. The application of research results has made it possible to improve effectiveness of the heat recovery systems by 3–4 % on average.

An analysis of the scientific literature [1–5] that we performed has revealed that not enough attention has been paid to date to the practical application of results from exergetic research. The integrated approaches considered in papers [6–9] do not make it possible to differentiate exergetic losses in a plant and to employ results of research in order to identify the conditions under which the level of losses would be minimal. To solve these problems, it is possible to apply an integrated approach that combines exergetic methods with the methods of thermodynamics of irreversible processes. Such an approach would make it possible to separate the losses of exergetic power in a plant based on causes and regions of their localization, to select exergetic losses related to heat transfer, and to define the thermophysical and modal parameters under which losses would be minimal. The application of a given approach would provide an opportunity to identify ways to improve the effectiveness of heat recovery systems in boiler plants.

3. The aim and objectives of the study

The aim of this work is to determine the losses of exergetic power in heat transfer processes in a plate air heater based on an integrated approach that would make it possible to separate the specified losses for causes and regions of their localization, as well as to determine values for the thermophysical and mode parameters under which these losses could be minimal. That would make it possible to improve the efficiency of the air heater.

By applying the proposed procedure, we have derived an analytical dependence of the losses of exergetic power in the processes of heat transfer in the plate of an air heater on its thermophysical parameters.

To accomplish the aim, the following tasks have been set:

– to devise a procedure for calculating the losses of exergetic power in the processes of heat transfer in the air heater of a heat recovery system after the boiler VK-21-M2 (KSVa-2.0G) and to construct a dependence of these losses on the thermophysical parameters of the air heater in the analytical form;

– to determine the magnitudes of losses of exergetic power under different thermophysical parameters of the air heater and different operational modes of the boiler and to establish the contribution of these losses in the processes of heat transfer to the total losses of exergetic power;

– to identify the regions of change in the thermophysical parameters and operational modes of the boiler at which the losses of exergetic power in the heat transfer processes are minimal.

4. Methods to study the effectiveness of a gas-air heat recovery plant

We have investigated regularities of change in the effectiveness of the plate air heater in a heat recovery system of the boiler unit based on the analysis of losses of exergetic power in the heat transfer processes. These losses were determined using the devised procedure based on the application of an integrated approach that combines exergetic methods and the methods of thermodynamics of irreversible processes.

5. Results of studying the effectiveness of a plate air heater in the heat recovery system

5. 1. Development of procedure for calculating the losses of exergetic power in the processes of heat transfer in the air heater of a heat recovery system after the boiler VK-21-M2 (KSVa-2.0G)

The examined plate air-heating heat recovery unit (air heater) is part of the system of heat recovery in the heating boiler VK-21-M2 (KSVa-2.0G), designed for heating blowing air (Fig. 1).

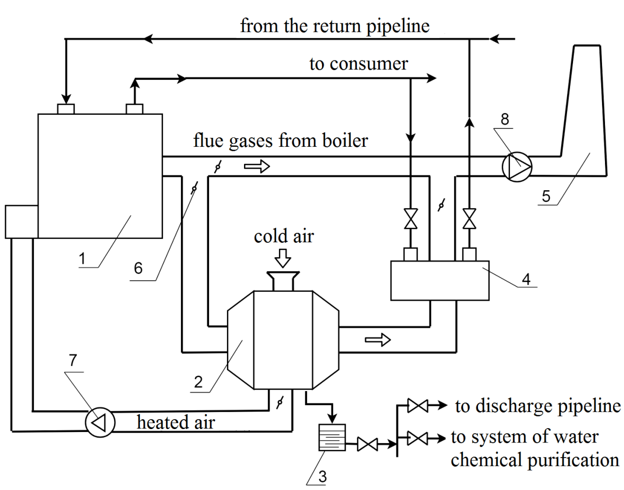

Fig. 1. Main diagram of the boiler unit with a system of heat recovery of the boiler's flue gases: 1 — heating boiler; 2 — air heater; 3 — condensate collector; 4 — gas heater; 5 — chimney; 6 — gate; 7 — fan; 8 — smoke exhauster

In the examined heat recovery system, gas heater 4 is applied in order to protect the gas discharge tracts of the boiler from condensate formation.

To devise a procedure for the calculation of losses of exergetic power in the plate of an air heater, we employed a mathematical model that includes a differential equation of exergy balance and the equation of thermal conductivity for a plate under boundary conditions of the third kind [7–9]:

$$\rho\frac{de}{dt}=-\frac{\partial}{\partial x}\left[q\left(1-\frac{T_0}{T}\right)\right]+q_v\left(1-\frac{T_0}{T}\right)-\frac{T_0}{T^2}q\frac{\partial T}{\partial x}, \quad (1)$$

$$q=-\lambda\frac{\partial T}{\partial x}, \quad (2)$$

$$c\rho\frac{\partial T}{\partial t}=\lambda\frac{\partial^2 T}{\partial x^2}+q_v, \quad (3)$$

$$T\big|_{t=0}=T_0, \quad (4)$$

$$-\lambda\frac{\partial T}{\partial x}\bigg|_{x=0}=\alpha_1\left(\theta_1-T_{x=0}\right), \quad (5)$$

$$\lambda\frac{\partial T}{\partial x}\bigg|_{x=\delta}=\alpha_2\left(\theta_2-T_{x=h}\right), \theta_2=T_0. \quad (6)$$

In the right-hand part of equation (1) the expression under the sign of the derivative is the flow of heat exergy, the second term is the exergetic power of internal heat sources, and the third term is the losses of exergetic power associated with thermal conductivity, viscosity of phases, inter-phase heat exchange, friction between phases, etc.

Here, c, λ, ρ are the specific heat capacity, thermal conductivity coefficient, and density of the plate's material; e is the specific exergy; q is the heat flux density; q_v is the density of internal sources of energy; T is the temperature of the plate; T_0 is the initial temperature; t is time; x is a coordinate; α_1, α_2 are the coefficients of heat release from a wall of the plate to air and flue gases, respectively; θ_1, θ_2 are the temperatures of air and flue gases; δ is the plate's thickness.

The losses of exergetic power for the entire system of volume V are determined in the following way:

$$E_{loss}=-T_o\int\limits_V\frac{q}{T^2}\frac{\partial T}{\partial x_i}dV=T_o\lambda\int\limits_V\frac{1}{T^2}\left(\frac{\partial T}{\partial x_i}\right)^2dV. \quad (7)$$

The result of solving (1) to (7) is the derived dependences for calculating the losses of exergetic power associated with the processes of heat transfer in the plate with a thickness of δ without internal heat sources for the established mode under boundary conditions of the third kind:

$$E^h_{loss}=\frac{T_o\lambda F}{\delta}\left[\begin{array}{l}\dfrac{2K-L}{-G(K-L+R)}-\dfrac{L}{GR}-\\ -\dfrac{2K}{G\sqrt{G}}\ln\dfrac{\left(2K-L-\sqrt{G}\right)\left(-L+\sqrt{G}\right)}{\left(2K-L+\sqrt{G}\right)\left(-L-\sqrt{G}\right)}\end{array}\right]; \quad (8)$$

$$Bi_1=\frac{\alpha_1\delta}{\lambda},\quad Bi_2=\frac{\alpha_2\delta}{\lambda}.$$

$$A=\mathrm{Bi}_1\mathrm{Bi}_2;\quad B=\mathrm{Bi}_1+\mathrm{Bi}_2+\mathrm{Bi}_1\mathrm{Bi}_2;\quad C=\mathrm{Bi}_1+\mathrm{Bi}_2;$$

$$D = \mathrm{Bi}_1;\quad K = A/B;\quad P = (D + A)/A;$$

$$N = (C + A)/B;\quad L = PK + N;$$

$$M = \theta_2 B/A(\theta_1 - \theta_2);$$

$$R = M + PN;\quad G = L^2 - 4KR,$$

where F is the area of the plate; upper index: h is the heat transfer; lower index: loss – are the losses.

5. 2. Calculation of losses of exergetic power in an air heater under different thermophysical parameters of the air heater and operational modes of the boiler

According to the derived estimation formula (8), we determined losses of exergetic power in the plate air heater (with 40 plates the size of 1×1 m) depending on thermal conductivity coefficient λ, convective heat transfer coefficient from the side of flue gases α_2 under different operational modes of the boiler (Fig. 2–5). We have considered seven operational modes of the boiler in a sequence from its maximum to its minimum load over a heating season. In this case, we took into consideration that, according to the regulations, if the boilers heat load is 50 % of the rated, the respective number of boilers are set to the rated mode with a decrease in the total number of operating boilers [10]. The source data to solve the problem were consistent with the regime card of the examined boiler VK-21-M2 (KSVa-2.0G) (Table 1). Calculation of total losses of exergetic power in the air heater was conducted according to formula (9):

$$E_{loss}^{com} = G_{fg}\left[c_{fg}\left(T_{fg}^{in} - T_{fg}^{out}\right) - T_c\left(c_{fg}\ln\frac{T_{fg}^{in}}{T_{fg}^{out}} - \frac{R}{\mu_{fg}}\ln\frac{p_{fg}^{in}}{p_{fg}^{out}}\right)\right] - G_a\left[c_a\left(T_a^{out} - T_a^{in}\right)\right] - T_c\left(c_a\ln\frac{T_a^{out}}{T_a^{in}} - \frac{R}{\mu_a}\ln\frac{p_a^{out}}{p_a^{in}}\right), \qquad (9)$$

where G is the consumption of heat carriers; p is pressure; R is a gas constant; T_c is the ambient temperature; μ is molecular weight; upper indices: in – input, out – output; lower indexes: fg – flue gases; a – air.

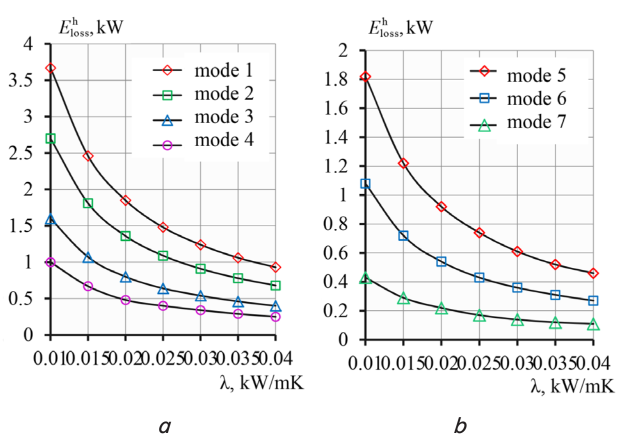

Fig. 2. Dependence of losses of exergetic power E^h_{loss} in the heat transfer processes under various operational modes of the boiler on the plate's thermal conductivity coefficient λ: *a* – modes 1–4; *b* – modes 5–7

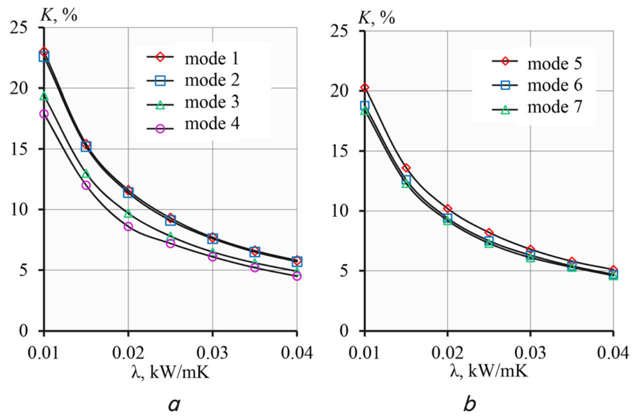

Fig. 3. Dependence of relative contribution K of the losses of exergetic power in the processes of heat transfer to the total losses of exergetic power in an air heater under different operational modes of the boiler on the plate's thermal conductivity coefficient λ: *a* – modes 1–4; *b* – modes 5–7

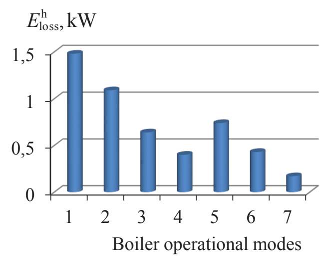

Fig. 4. Losses of exergetic power in the heat transfer processes E^h_{loss} in an air heater under different operational modes of the boiler at λ=0.025 kW/mK

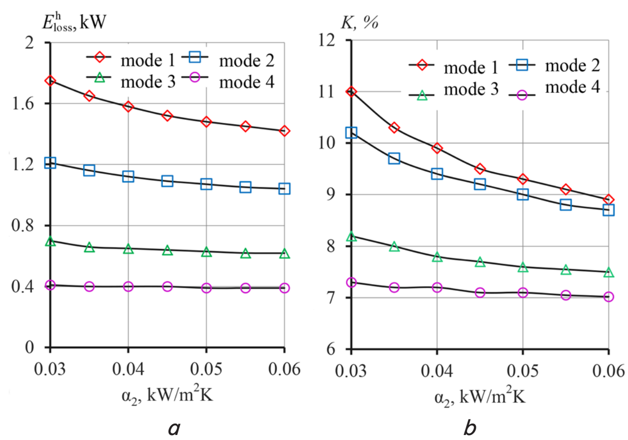

Fig. 5. Dependence on a convective heat transfer coefficient from the side of flue gases α_2: *a* – losses of exergetic power E^h_{loss}; *b* – relative contribution K of the losses of exergetic power in the processes of heat transfer to the total losses E^{com}_{loss} in an air heater

5. 3. Determining the regions of change in the thermophysical parameters and operational modes of the boiler at which the loss of exergetic power in the heat transfer processes are minimal

Fig. 2 shows that the examined air heater demonstrates a significant dependence of losses of exergetic power in the heat transfer processes on its thermal conductivity coefficient λ and operational modes of the boiler.

Table 1

Source data for the calculation of losses of exergetic power in an air heater

Parameter	Operational modes of the boiler VK-21-M2 (KSVa-2.0G)						
	1	2	3	4	5	6	7
T_{fg}^{in}, °C	156.8	145.5	133.2	120.0	130.8	116.5	95.3
T_{fg}^{out}, °C	83.8	77.1	71.5	64.5	76.6	69.0	57.9
T_{a}^{in}, °C	–20.0	–15.0	–10.0	–5.0	0	5.0	10.0
T_{a}^{out}, °C	66.4	65.7	62.7	60.3	63.8	60.8	55.5
p_{fg}^{out}, kPa	100.45	100.56	100.67	100.77	100.44	100.60	100.79
p_{fg}^{in}, kPa	99.60	99.67	99.78	99.84	99.62	99.72	99.85
Gfg, kg/s	0.91	0.81	0.70	0.60	0.91	0.78	0.57
Ga, kg/s	0.83	0.73	0.64	0.54	0.83	0.71	0.52

In Fig. 2, the curves illustrating the losses of exergetic power in an air heater depending on the plate's coefficient of thermal conductivity λ demonstrate two distinct regions for all operational modes of the boiler. Along the first region, a changing in the coefficient λ from 0.04 kW/mK to 0.025 kW/mK leads to a relatively slight increase in the losses of exergetic power in an air heater (0.1...0.6 kW). Along the second region, a change in the coefficient of thermal conductivity from 0.025 kW/mK to 0.01 kW/mK results in that the losses of exergetic power in an air heater increase relatively sharply. In this case, the transition from the first to the fourth and from the fifth to the seventh mode is accompanied by a decrease in the losses of exergetic power for all values of λ. It should be noted that at high values of the coefficient of thermal conductivity the dependence of losses of exergetic power on the boiler operating mode is less evident than at low thermal conductivity coefficients. A similar pattern is observed for the dependence of relative contribution of the losses of exergetic power in the heat transfer processes $K = E_{\text{loss}}^{\text{h}} 100\,\% / E_{\text{loss}}^{\text{com}}$ to the total losses of exergetic power $E_{\text{loss}}^{\text{com}}$ in an air heater on the thermal conductivity coefficient (Fig. 3). However, in this case, there are minor differences in the relative contribution of these losses under different operational modes of the boiler. Thus, the study has shown that the lowest losses of exergetic power characterize the region of change in the coefficient of thermal conductivity from 0.025 kW/mK to 0.040 kW/mK, as well as the regions from the third to the seventh working mode of an air heater.

It should be noted that the heat transfer coefficient α_2 from the side of flue gases exerts a relatively small impact on the losses of exergetic power in the heat transfer processes in a plate within a single operational mode of the boiler (Fig. 5). In this case, according to the data obtained, a transition from the first to the seventh mode is accompanied by a somewhat less pronounced decrease in the losses of exergetic power with an increase in the values for α_2. The dependence of the relative contribution of losses of exergetic power in the heat transfer processes in a plate to the total losses on this coefficient is generally the same as on the coefficient of thermal conductivity.

6. Discussion of results of studying the effectiveness of a plate air heater

The integrated approach, employed for the air heater of a heat recovery system after the boiler VK-21-M2 (KSVa-2.0G), in contrast to alternatives [6–9], has made it possible to separate, in the examined air heater, the losses of exergetic power for causes and regions of their localization, and to identify losses due to heat transfer. For the examined air heater, the analytical dependence of these losses on thermophysical parameters, derived as a result of solving jointly a differential equation of exergy and the thermal conductivity equation, has made it possible to establish patterns in a change in the specified losses on the plate's thermal conductivity coefficient and the coefficient of convective heat transfer from the side of flue gases under different operational modes of the boiler. The advantage of a given approach, compared with the approaches outlined in [1–5], is a possibility to apply our research findings in order to improve efficiency of the air heater by determining the region of change in the thermophysical and regime parameters at which the level of losses of exergetic power in the air heater would be minimal.

The thermal conductivity coefficients' range from 0.025 kW/mK to 0.040 kW/mK, which corresponds to the lowest losses of exergetic power in an air heater, is matched by the stainless steel of various types (chromium, chromium molybdenum, chromium-nickel, etc.). The type and grade of steel are defined when designing appropriate heat exchangers depending on the need to ensure their other characteristics (acid and temperature-resistance, strength, etc.). At present, the fabrication of the packages of plates for heat recovery units, along with the traditionally used materials, successfully exploits the polymeric micro- and nanocomposites, which possess a wide range of thermophysical characteristics.

The present research has been performed into the air heater that is composed of the packages of plates. The application of this approach to analyze the losses of exergetic power in heat recovery units of different types should involve, in each particular case, the consideration of certain boundary conditions for a thermal conductivity equation and the derivation of appropriate analytical or numerical solutions through by solving jointly a differential equation of exergy and the thermal conductivity equation.

Our research could be developed in the direction of improvement of the procedure for analyzing the heat recovery units' efficiency, which combines exergetic methods with the methods of thermodynamics of irreversible processes. It is advisable to obtain values for the exergy dissipators that would make it possible to separate losses of exergetic power due to heat transfer and to determine hydrodynamic losses during motion of heat carriers. That would make it possible to establish the contribution of each exergy dissipator to the total losses in an air heater and to define the basic characteristics of the air heater that ensure the minimum level of losses.

7. Conclusions

1. By using an integrated approach, combining exergetic methods with the methods of thermodynamics of

irreversible processes, we have devised a procedure for calculating the losses of exergetic power in the heat transfer processes in the plate air heater of a heat recovery system after the boiler VK-21-M2 (KSVa-2.0G). The procedure makes it possible, by using a joint solution to the differential equation of exergy and the thermal conductivity equation, to derive an analytical dependence of the losses of exergetic power in the heat transfer processes in a plate heater on its thermophysical parameters.

2. Based on the devised procedure, we have determined magnitudes of losses of exergetic power in the plate of an air heater and the contribution of these losses in the processes of heat transfer to the respective cumulative losses. We have established dependences of these losses on the plate's thermal conductivity coefficient and a heat transfer coefficient from the side of flue gases for different operational modes of the boiler. It is shown that for all modes of operation of the boiler an increase in the thermal conductivity coefficient and the heat transfer coefficient from the side of flue gases leads to a decrease in the losses of exergetic power, which is associated with a decrease in the thermal resistance of heat transfer with an increase in these coefficients.

3. We have identified regions of change in the thermophysical parameters and operational modes of the boiler with a minimal level of losses of exergetic power. It is shown that the lowest losses of exergetic power are observed in the range of change in the plate's thermal conductivity coefficient from 0.025 kW/mK to 0.040 kW/mK and for a sequence of the examined operational modes of the boiler from the third to the seventh regime.

References

1. Sahin A. Z. Importance of Exergy Analysis in Industrial Processes. URL: https://www.researchgate.net/publication/228988818
2. Exergy analysis: An efficient tool for understanding and improving hydrogen production via the steam methane reforming process / Hajjaji N., Pons M.-N., Houas A., Renaudin V. // Energy Policy. 2012. Vol. 42. P. 392–399. doi: https://doi.org/10.1016/j.enpol.2011.12.003
3. Cziesla F., Tsatsaronis G., Gao Z. Avoidable thermodynamic inefficiencies and costs in an externally fired combined cycle power plant // Energy. 2006. Vol. 31, Issue 10-11. P. 1472–1489. doi: https://doi.org/10.1016/j.energy.2005.08.001
4. Jiang Y. Y., Zhou S. X. Exergy Analysis of Boiler Based on the Temperature Gradient // 2010 Asia-Pacific Power and Energy Engineering Conference. 2010. doi: https://doi.org/10.1109/appeec.2010.5449523
5. Tsatsaronis G., Morosuk T. Advanced thermodynamic (exergetic) analysis // Journal of Physics: Conference Series. 2012. Vol. 395. P. 012160. doi: https://doi.org/10.1088/1742-6596/395/1/012160
6. Morosuk T., Tsatsaronis G. A new approach to the exergy analysis of absorption refrigeration machines // Energy. 2008. Vol. 33, Issue 6. P. 890–907. doi: https://doi.org/10.1016/j.energy.2007.09.012
7. The efficiency analisis of heat utilization instalasion for heating and humidifying of combustion air of boiler plant / Fialko N., Stepanova A., Presich G., Gnedash G. // Industrial Heat Engineering. 2015. Vol. 37, Issue 4. P. 71–79. URL: http://dspace.nbuv.gov.ua/bitstream/handle/123456789/142191/08-Fialko.pdf?sequence=1
8. Efficiency for heat utilizing systems of boiler instalation, for optimization of method of different types / Fialko N., Stepanova A., Navrodskaya R., Sherenkovsky J. // Industrial Heat Engineering. 2014. Vol. 36, Issue 1. P. 41–46.
9. Thermodynamic optimization and analysis of the efficiency of heat recovery system of boiler / Fialko N., Stepanova A., Presich G., Navrodskaya R., Sherenkovskiy Yu. V., Maleckaya O. E., Gnedash G. A. // Industrial heat engineering. 2012. Vol. 34, Issue 2. P. 59–66. URL: http://dspace.nbuv.gov.ua/bitstream/handle/123456789/59078/09-FialkoNEW.pdf?sequence=1
10. Kuznetsov N. V., Mitor V. V., Dubovskiy I. E. Heat calculation of boiler units. Kyiv: Publisher Ekolit, 2011. 296 p.