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ENERGY AND EXERGY EFFICIENCY ANALYSIS OF COMBINED HEAT AND POWER PLANT

Introduction

Due to the high energy prices and reduction of fossil fuels, energy saving is one of the most serious tasks. Therefore, improving the sources and systems of energy supply is important in solving these problems.

Nuclear and thermal power plants are the two main types of power generation in the Ukrainian energy system. In addition, thermal power plants (combined heat and power plants that simultaneously produce heating, hot water and electricity), as well as hydroelectric power stations and PSPPs (pumped storage stations) occupy a prominent place in the balance of the Ukrainian electric power industry. According to the results of 2015, the structure of generating capacities in Ukraine was distributed as follows: 50 % was accounted for by TPPs, 25 % — at NPPs, 12 % — at CHPPs, 11 % — at HPPs and PSPPs, and about 1 % were occupied by various alternative sources, including solar, wind and biogas plants [1].

Existing urban energy supply systems based on large steam turbine thermal power plants are gradually degrading as a result of physical and moral deterioration of equipment, the complexity of the technical re-equipment of stations and networks using advanced technologies.

Under the second itions, reconstruction, modernization and optimization of energy supply systems is one of the most important. First of all, reconstruction of physically worn-out thermal power plants built in the 1950s is necessary. Reconstruction and modernization involves the replacement of steam turbine equipment with gas turbine and gas-vapor plants, the possibility of transferring part of the heat load to small CHPP with gas piston and gas turbine engines.

In this regard, the study of the effectiveness of various options for the technical re-equipment of existing CHPPs is relevant.

A variety of methods are used to analyze the efficiency of the CHPPs, which differ in essence. Currently, two methods of thermodynamic analysis of thermotechnological processes and systems have been developed: the method of cycles and the exergy method [2–4].

The essence of the cycle method is to establish a relationship between energy flows (heat) with the technical parameters of processes based on I and II laws of thermodynamics. The cycle method does not consider the qualitative differences in energy flows and the features of technological processes, which is its drawback. This method does not take into account that heat of different potentials has different values, it does not allow to detect the main foci of irreversibility, that is, processes that should attract attention in order to increase efficiency.

The exergy analysis method is devoid of this drawback and is the most promising, it allows you to take into account both the properties of the system itself and the environment. The exergy analysis indicates the location, magnitude and sources of thermodynamic irreversibility in the energy-converting system. The goals of the exergy method for analyzing technological systems and processes are:

1) studying of the conversions of working energy for thermal systems in general, the distribution of exergy losses for the entire thermal system and for each component;

2) optimization of the whole scheme and those nodes where the exergy losses are greatest, determination of rational modes and external conditions of the system.

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Exergy analysis provides an idea and an opportunity to find the reasons for the inefficiency of a thermodynamic system.

Darnitsa combined heat and power plant is chosen for analysis.

Crux of problem

The aim of the study is to analyze the efficiency of thermal power plants by the exergy method, to determine measures to increase the thermal efficiency of thermal power plants and to choose a rational option for the reconstruction of thermal power plants with physically worn steam turbine equipment.

Analysis of recent research and publications

The reliability of technical and economic information is particularly important when assessing the efficiency of simultaneous production of electricity and heat. If there are well-developed methods to ensure compliance of efficiency estimates with the laws of energy conversion for technological schemes and plants producing one type of energy, then for plants producing electrical and thermal energy the problem of evaluating the efficiency has not been solved completely. The lack of an effective method has a negative impact on the development of energy and leads to the irrational use of fuel and energy resources [2]. In the works of Andryushchenko [3], Brodyansky [4], Shargut [5], Khlebalin [6], Morosuk [7] and others the basic principles of exergy analysis, methods of exergy balances and exergy losses calculation for technical systems, modeling of exergy distribution between power units have been developed and implemented in engineering practice. In work [8] authors offered the technique of drawing up the energy balance for research of various technical systems. The method is constructed on the basis of the first and second laws of thermodynamics. The technique is based on the using of the concepts of chemical energy and exergy of substances. The energy balance composed according to this method allows to take into account all types of energy, including chemical energy of fuel, raw materials, products and waste of the object under consideration.

The exergy method is developed in the article [9]. The authors propose to simplify the definition of thermal and economic efficiency of combined heat and power plant. The authors consider the combined plant as a generator of an exergy of various energy carrier flows (steam, hot water). It is proposed not to divide the equipment into those related to electricity or heat generation, since a turbine, an electric generator and a transformer, a network pump and a network heater are just as necessary for both steam generation and electricity generation.

The method has found further development (for example, in the works [10, 11, 12]). The method of exergy analysis is the most rational for assessing the energy efficiency of combined heat and power plants. Exergy analysis is used in this work to assess the thermodynamic efficiency of processes and their parts, as well as sources of losses. Exergy and energy analysis allows to identify losses and ways to eliminate them.

Darnitsa combined heat and power plant description

Kiev CHPP-5 is the largest cogeneration power plant. The electric capacity of the CHPP is 700 MW, the thermal capacity is 1874 Gcal/h. At the first stage of the thermal power plant, two heating units with a capacity of 100 MW each, two energy gas-oil boilers with a capacity of 480 t/h of steam and two peak hot-water boilers with a capacity of 180 Gcal/h of heat were installed.

On the second stage, two heating turbine units with a capacity of 250...300 MW, two boilers with a capacity of 1000 t/h of steam and one peak hot water boiler with a capacity of 180 Gcal/h of heat are installed. The main fuel of the CHPP is coal ASH, the reserve is natural gas. Direct-flow technical water supply system. Its main purpose is the heat supply of the city.

Currently, Kiev CHPP-5 provides hot water supply and centralized heating to five districts of the capital: Darnitsky, Solomensky, Pechersky, Goloseevsky and Shevchenkovsky. Hot water and heat from this CHPP also goes to a number of residential areas, in particular to Osokorki, Poznyaki, Rusanovka, Bereznyaki, Teremki, as well as the Kharkiv housing estate.

The station has a modernization program until 2020, it is planned to reconstruct and increase the installed capacity of the CHPP by building three blocks of Siemens combined cycle plants with a capacity of 47 MW each [13].

Schematic layout of the equipment of the Darnytsa CHPP is shown in Fig. 1 [12].

It represents a complex of technological equipment, consisting of 4 turbogenerators, having selections for production and heating purposes, 3 condensers, hot water boilers, power boilers and deaerators.

The energy of fossil fuels is converted into electricity and heat in form of hot water or steam, which are used by household and industrial consumers. In boilers the internal energy of combusted fossil fuels is transferred to the chemically purified water, what transforms into steam. In turbine potential steam energy turns into kinetic energy of rotation of the turbine rotor.

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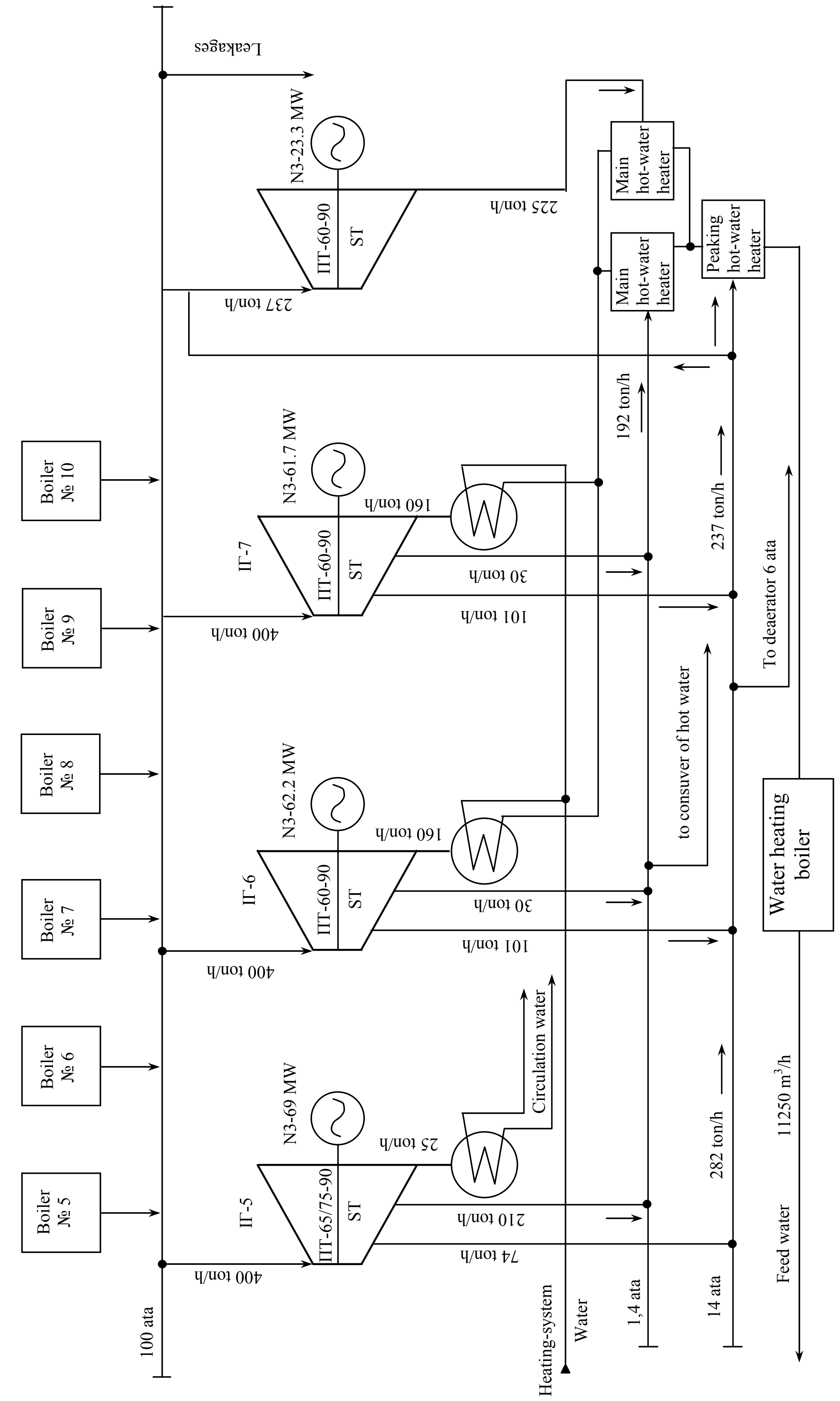

Fig. 1. Schematic layout of the equipment of the Darnytsa CHPP

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As a result, mechanical energy is converted into electrical energy and transmitted to external electric networks.

The baseline data of the Darnitsa coal based combined heat and power plant [12] are given in Table 1.

Table 1

The Plant operation parameters

Feed water inlet temperature to boiler	t, °C	215
Steam flow rate	D, ton/h	398
Steam temperature	t, °C	540
Steam pressure	p, MPa	10
Pressure in condenser	p, MPa	0.0058
Nominal steam flow rate in production selection	Q_{ps}, ton/h	155
Nominal steam flow rate in heating selection	Q_{hs}, ton/h	130
Production selection pressure	p_{ps}, MPa	1.274
Heating selection pressure	p_{hs}, MPa	0.118
Electric Power output	N, MW	180
Output heating and hot water supply	Q, GCal/h	448
Fuel consumption	B, tn/h	22
Lower heating value	Q, kJ/kg	5300
Specific heat consumption per kW·h generated	Q_{hc}, ccal/kW·h	1389,4
Specific consumption of equivalent fuel per kWh·h generated.	Q_f, ccal/kW·h	282.4

Thermodynamic model of CHPP is based on Rankine cycle. The *T-s* diagram of the Cycle of the power plant is shown in Fig. 2. The principal states of the technological process are shown on the diagram.

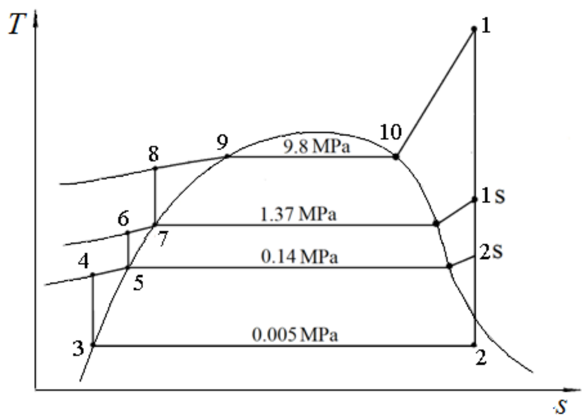

Fig. 2. Rankine cycle of CHPP

The superheated steam at pressure of 9.8 MPa enters the turbine at state 1 and expand. A fraction of the total flow is extracted at points 1s and 2s. The rest of the steam expands through the turbine to state 2. This portion of the total flow is condensed to saturated liquid at state 3. The saturated liquid is pumped by the condensate extraction pump. Finally, after increasing the temperature by the feed water heater and increasing the pressure by the boiler feed pump to the steam generator pressure working fluid enters the steam generator at state 8 and is heated in the steam generator at constant pressure to state1.

The method of analysis

Main stages of the analysis and making of decisions:

- analysis of all energy resources and energy carriers, including secondary ones, within one technological process and determination of their thermodynamic parameters;
- determination of energy and exergy losses at all stages of the conversion and use of energy in all elements of technological schemes;
- determination of energy and exergy indicators of technological processes and the degree of thermodynamic perfection of technical systems, installations, devices based on design and operational data.

Part of the energy of a system that can be converted into energy of organized forms is called exergy. The measure of exergy is the maximum useful work that can be obtained with a reversible change in state system from a given (with parameters p, T) to a state of equilibrium with the environment at parameters p_0 and T_0. Thus, unlike energy, exergy is not only a function system parameter, but also environmental parameters [14]. So, exergy analysis is a thermodynamic method of a system considered in the interaction with the environment.

The exergy and energy analysis of the coal based thermal power plant have been done. In order to perform the exergy analysis of the plant, the detail steam properties, mass, energy and exergy balances for the components of plant were calculated.

The general performance criteria are power output and thermal efficiency. These parameters are also decisive performance criteria in the economic analysis of power plants.

Energy efficiency of a cycle:

$$\eta_{cycle} = \frac{[(h_1 - h_2) - \alpha_2(h_{02} - h_2) - \alpha_1(h_{01} - h_1) - l_p]}{h_1 - h_8},$$

where h — enthalpy in ascertain point; α — steam extraction; l_p — work of a pump.

According to calculations, η_{cycle}= 0.32. We denote that mechanical losses in turbine are: η_t = 0.98, mechanical and electrical losses in generator are: η_g = 0.98, energy efficiency of a boiler installation is: η_b = 0.91, energy efficiency of steam pipes: η_{sp} = 0.99.

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Heat of fuel combustion in the boiler:

$$q_{fuel} = \frac{BQ_L^f}{D},$$

where B — fuel consumption; Q_L^f — lower heating value of fuel; D — steam consumption.
Heat losses in a boiler:

$$\Delta q_b = (1 - \eta_b) q_{fuel}.$$

Mechanical losses in turbine:

$$\Delta q_t = \eta_b \eta_{sp} \eta_c (1 - \eta_m) q_{fuel}.$$

Heat losses in condenser:

$$\Delta q_c = \eta_b \eta_{sp} (1 - \eta_g) q_{fuel}.$$

In this study exergy efficiency and exergy destruction rate of both the plant and plant component are determined.

Evaluation of the efficiency of energy processes is carried out on the basis of exergy balances, reflecting the equality of exergy supplied to the system, exergy taken away from it and its losses. To compile an exergy, balance the technological scheme of the plant (see Fig. 1) is considered. Exergy balance can be written as:

$$\sum e_{input} = \sum e_{output} + \sum e_{losses},$$

where e_{input} — total exergy at the entrance, including exergy of matter, energy flow, heat, fuel, etc; e_{output} — total exergy at the exit; e_{losses} — total exergy of losses.

Exergy in each point of the cycle:

$$e = (h - h_0) - T_0 (S - S_0),$$

where h — entropy in a certain point; h_0 — enthalpy of the environment; S — entropy of the environment; S_0 — entropy in a certain point; T_0 — temperature of the environment.

Exergy of a fuel:

$$e_{fuel} = q_{fuel}\left(1 - \frac{T_0}{T}\right).$$

The exergy losses were calculated in the boiler, feed water heaters, steam turbines and condensers. The exergy losses for steam turbine and condenser can be calculate by knowing the thermodynamic properties of inlet and outlet flow of the steam and using exergy balance equation.

Exergy losses in turbine:

$$e_t = e_{imput} - e_{output} - l.$$

Exergy losses in condenser:

$$\Delta e_c = e_{imput} - e_{output}.$$

Exergy losses in the boiler:

$$e_b = e_{imput} + e_{input}^{fuel} - e_{output}.$$

Fuel is coal, the lower heating value of coal is Q_L^f = 27 230 kJ/kg, exergy e_f = 29 410 kJ/kg, and as coal is solid fuel then e_f / Q_L^f = 1.08.

Heat transfer at a finite temperature difference is an irreversible process, associated with an increase in entropy and the loss of part of the maximum possible work.

In this regard, the main indicator of the exergy method is exergy efficiency [4; 9], which is equal to the ratio of leaving exergy stream to the total entering exergy streams.

$$\eta_e = \frac{e_{input} - e_{output}}{e_{input}} 100\ \%.$$

When equating the energy and exergy balance, the losses associated with the heat exchange in the water heaters of heating-system water were not taken into account.

Comparison of Energy **and Exergy Efficiency**

Energy and exergy efficiencies of the overall power plant were carried out for 50 % and100 % of loading condition for the design data.

The exergy analysis has been carried out for components of the plant, to evaluate the exergy losses in the individual component and then the exergy analysis for the overall plant has been carried out and the total plant exergy losses have been computed.

The energy and the exergy losses of the systems have been determined using their mass, energy and exergy balance equations.

The energy and exergy efficiencies calculated for the individual components as well as for the entire plant are shown in Fig. 3 and Fig. 4. Exergy losses of the power plant components are shown in Fig. 5. The first column of tables corresponds to a load of 100 %, and the second column corresponds to a load of 50 %.

Energy efficiency of power plant is 55 % at 100 % of loading condition and 58 % of 50 % of loading condition. Consideration of the exergy balance shows that the total CHPP exergy efficiency is 35 % and 49 %, respectively for loads of 100 and 50 %.

The exergy analysis shows that the boiler has the largest exergy loss. Feed water heaters have the second largest exergy loss.

The relatively low exergy efficiency of the boiler is due to significant losses occurring in the process of heat transfer from fuel with high potential chemical energy to low-potential steam.

The exergy balance of the boiler makes possible not only to estimate the quality of the heat expended and all losses found from the heat balance, but also to identify losses that are not reflected in the heat balance. Such losses are losses due to the irreversibility of fuel combustion, due to the irreversibility of heat exchange during mixing.

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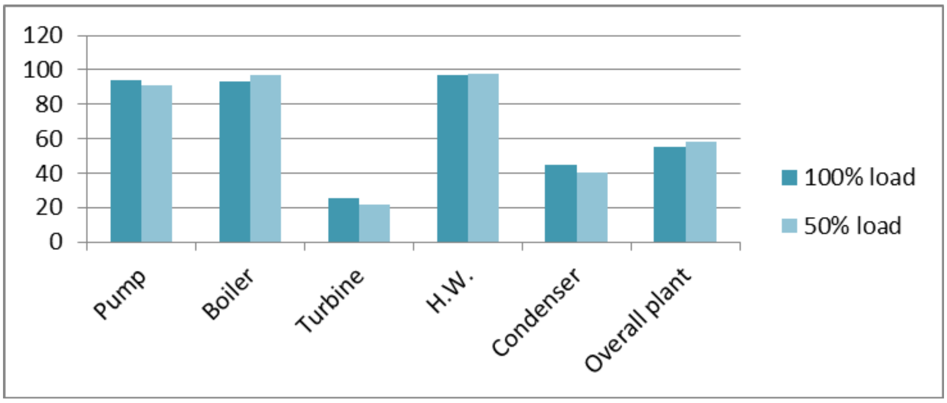

Fig. 4. Energy efficiency for plant components

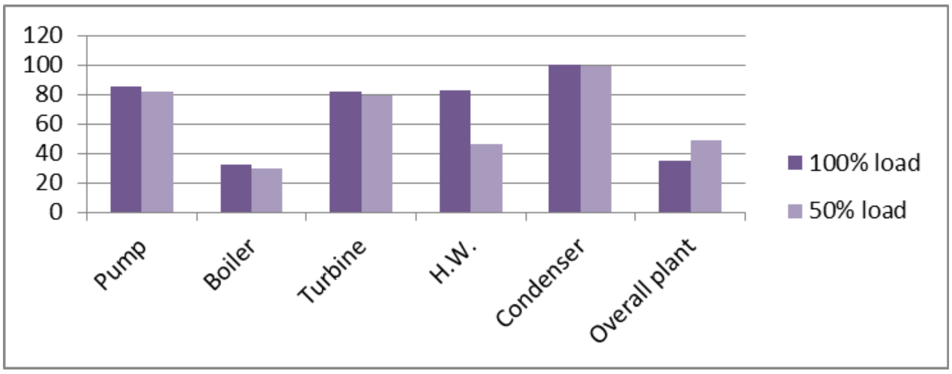

Fig. 5. Exergy efficiency for plant components at different loads

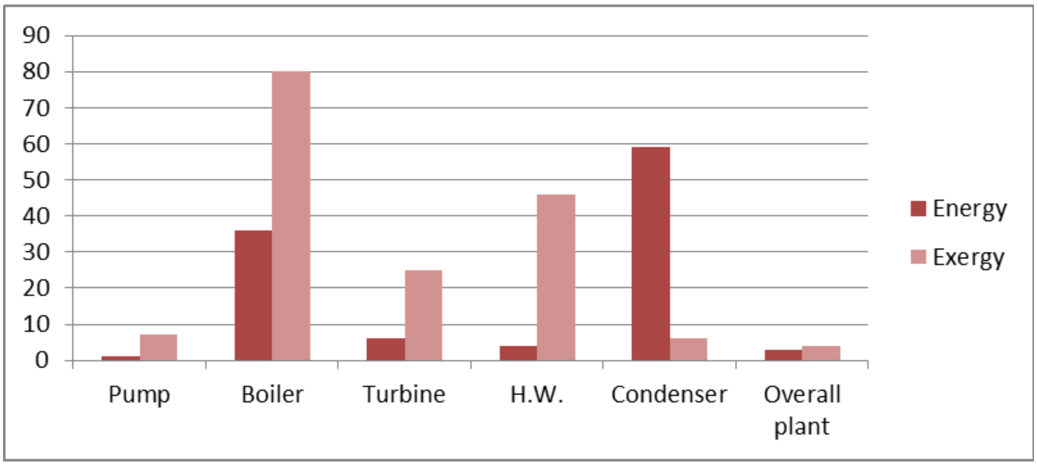

Fig. 6. Energy and exergy losses

Conclusion

The analysis presented in this paper demonstrates the application of energy and exergy concept to investigate combined heat and power plant.

From Fig. 5, it is seen that the greatest loss of energy (59,2 %) occurred in the condenser. Thus, from the point of view of energy analysis reduction of losses in the condenser can lead to improved performance of CHPP such an erroneous conclusion may lead to an incorrect choice of the direction of modernization, as any improvements in the condenser cannot be done. The biggest exergy loss was in the boiler, up to 80.3 % of total exergy loss.

A small part of exergy loss occurs in the condenser. The obtained results show that the most critical component is the boiler unlike the results from energy analysis where the condenser is considered to be most critical.

Therefore, energy analysis cannot be used to determine the directions of modernization of CHPP to improve efficiency.

Exegetic analysis reveals the essence of energy transformations in the CHPP as a whole and its components. Therefore, it is recommended to carry out the choice of the direction of modernization on the basis of economic and exergy analysis.

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From Fig. 5 it is seen that the largest energy loss (59.2 %) occurred in the condenser. Thus, from the point of view of energy analysis, a reduction in losses in the condenser can lead to increasing of the performance of the CHPP. Such an erroneous conclusion can lead to the wrong choice of the direction of modernization, since no improvements in the condenser can be made.

The greatest exergy losses occur in the boiler (up to 80.3 % of the total exergy loss). A small portion of the exergy loss occurs in the condenser. The results show that the boiler is the most critical component, unlike the energy analysis results, where the condenser is considered the most critical.

Therefore, energy analysis cannot be used to determine the direction of modernization of thermal power plants to improve production efficiency. Exergy analysis reveals the essence of energy transformations in a thermal power plant as a whole and its parts.

Therefore, the choice of the direction of modernization is recommended on the basis of economic and exergy analysis.

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ЕНЕРГЕТИЧНИЙ І ЕКСЕРГЕТИЧНИЙ АНАЛІЗ ТЕПЛОЕЛЕКТРОЦЕНТРАЛІ

У статті наведено енергетичний і ексергетичний аналіз теплоелектроцентралі. Ексергетичний аналіз ґрунтується на взаємодії системи з навколишнім середовищем. Це сприяє більш точному дослідженню енергетичної установки, виявлення вузлів з найбільшими втратами.

Для дослідження обрана теплофікаційна схема Дарницької ТЕЦ. Для розрахунків взято ланцюг технологічної схеми, що складається з котла, турбіни з двома відборами на теплофікаційні і виробничі потреби, конденсатора і насоса. На підставі робочих параметрів обладнання Дарницької ТЕЦ проведено енергетичний і ексергетичний аналізи, виявлені точки з найбільшими енергетичними втратами, проведена кількісна оцінка втрат енергії незалежно від природи джерела їх виникнення. Отримані розрахункові характеристики по ексергетичному і енергетичному аналізам показують розподіл втрат енергії як в окремих вузлах, так і для системи в цілому. У статті проведено порівняльні розрахунки і наведено графічне порівняння ККД і втрат енергії і ексергії при різному навантаженні станції. Показано, що в результаті такого аналізу об'єктивно відображені всі енергетичні перетворення, що відбуваються в технологічному ланцюгу теплоелектроцентралі, що служить основою для розробки заходів щодо вдосконалення досліджуваної системи і її оптимізації. Показано, що оптимізація будь-яких параметрів реального циклу установки полягає не в досягненні максимуму її ексергетичного ККД, а в знаходженні економічно найвигіднішого рішення.

Модернізації підлягає не кожна установка з найбільшими втратами.

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Так, наприклад, енергетичний аналіз вказує, що великі втрати відбуваються в конденсаторі. У той же час ексергетичний аналіз показує, що при даних параметрах навколишнього середовища удосконалення конденсатора не приведе до підвищення ефективності.

Ключові слова: енергія; ексергія; термодинамічний аналіз; енергетика; теплоелектроцентраль.

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ENERGY AND EXERGY EFFICIENCY ANALYSIS OF COMBINED HEAT AND POWER PLANT

The article provides energy and exergy analysis of the combined heat and power plant. Exergy analysis is based on the interaction of the system with the environment. This contributes to a more accurate study of the power plant, the identification of nodes with the greatest losses.

For the study, the heating scheme of the Darnitsa CHPP was selected. For calculations, we took a chain of a technological scheme consisting of a boiler, a turbine with two selections for heating and production needs, a condenser and a pump. Energy and exergy analyzes were carried out of the operating parameters of the equipment of the Darnitsa CHPP, points with the highest energy losses were identified. A quantitative assessment of energy losses was carried out regardless of the nature of the source of their occurrence. The obtained calculated characteristics for exergy and energy analysis show the distribution of energy losses both in individual nodes and for the system as a whole. The article provides comparative calculations and a graphical comparison of the efficiency and energy and exergy losses at different station loads. It is shown that as a result of such an analysis, all energy transformations occurring in the technological chain of the cogeneration plant are objectively reflected, which serves as the basis for the development of measures to improve the system under study and its optimization. It is shown that the optimization of any parameters of the real installation cycle does not consist in achieving the maximum of its exergy efficiency, but in finding the most economically advantageous solution. Not every installation with the greatest losses is subject to modernization. For example, energy analysis indicates that large losses occur in the capacitor. At the same time, an exergy analysis shows that with these environmental parameters, an improvement in the capacitor will not lead to an increase in efficiency.

Keywords: energy; exergy; thermodynamic analysis; energetic; combined heat and power plant.

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ЭНЕРГЕТИЧЕСКИЙ И ЭКСЕРГЕТИЧЕСКИЙ АНАЛИЗ ТЕПЛОЭЛЕКТРОЦЕНТРАЛИ

В статье приведён энергетический и эксергетический анализ теплоэлектроцентрали. Эксергетический анализ основывается на взаимодействии системы с окружающей средой. Это способствует более точному исследованию энергетической установки, выявлению узлов с наибольшими потерями.

Для исследования выбрана теплофикационная схема Дарницкой ТЭЦ. Для расчётов взята цепочка технологической схемы, состоящей из котла, турбины с двумя отборами на теплофикационные и производственные нужды, конденсатора и насоса. На основании рабочих параметров оборудования Дарницкой ТЭЦ проведены энергетический и эксергетический анализы, выявлены точки с наибольшими энергетическими потерями, проведена количественная оценка потерь энергии независимо от природы источника их возникновения. Полученные расчетные характеристики по эксергетическому и энергетическим анализам показывают распределение потерь энергии как в отдельных узлах, так и для системы в целом. В статье проведены сравнительные расчеты и приведено графическое сравнение КПД и потерь энергии и эксергии при разной нагрузке станции. Показано, что в результате такого анализа объективно отражены все энергетические превращения, происходящие в технологической цепочке теплоэлектроцентрали, что служит основой для разработки мероприятий по усовершенствованию исследуемой системы и ее оптимизации. Показано, что оптимизация каких-либо параметров реального цикла установки заключается не в достижении максимума ее эксергетического КПД, а в нахождении экономически наивыгоднейшего решения. Модернизации подлежит не каждая установка с наибольшими потерями. Так, например, энергетический анализ указывает, что большие потери происходят в конденсаторе. В то же время эксергетический анализ показывает, что при данных параметрах окружающей среды усовершенствование конденсатора не приведёт к повышению эффективности.

Ключевые слова: энергия; эксергия; термодинамический анализ; энергетика; теплоэлектроцентраль.

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