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EXERGY PINCH ANALYSIS OF ALL ELEMENTS OF THE BOILER UNIT AND THE BOILER UNIT AS A WHOLE

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The relevance *of the research is caused by the need to improve the energy efficiency of heating systems, since all types of fuel are becoming more expensive. In this regard, there is a need to create a method of thermodynamic improvement of heat engineering systems.*
The main aim *of the research is the creation of a method for improving heating systems, the application of this method on the example of a boiler unit PP-2650-255 GM.*
Objects: *a direct-flow boiler PP-2650-255 GM, for which a thermodynamic analysis of the processes occurring in individual elements of the boiler – an air heater, economizer, firebox, and superheater – is performed. The article analyzes all heat fluxes on each element of the boiler.*
Methods. *An exergy method of thermodynamic analysis is used as a research tool. It allows taking into account the energy potential of thermal processes. To date, the most effective method of parametric optimization of heat and power processes is the method of integration of heat flows (pinch method). However, the pinch method is based on a change in flow enthalpy, which does not take into account the qualitative characteristics of energy. In the article, the development of the pinch method continues; flow exergy is used instead of flow enthalpy. Optimization of heat engineering parameters is carried out using an exergy pinch method.*
Results. *Exergy pinch analysis allows you to identify unused exergy and determine in which part the loss occurs. According to the calculations and the graph, it can be seen that hot flows lost 1503,57 MW of exergy, cold flows took 1295,57 MW of exergy, taking into account cooling of the working fluid by bypass. Thus, 47,9 MW of unused exergy was detected in this boiler unit. The results of the exergy pinch analysis allow us to formulate and justify specific design measures to improve the energy efficiency of the boiler unit. This analysis allows you to effectively use the energy and resources of heating equipment.*

Key words:
Energy efficiency, exergy, exergy analysis, heat balance, exergy balance, pinch analysis.

Introduction

Currently, a fully developed approach has been developed to assess the energy efficiency of technical systems. This approach is based on the well-known methods of thermodynamic analysis – energy, entropy and exergy. Each of these methods has well-known advantages, disadvantages, and limitations.

The energy (enthalpy) method of assessing energy efficiency is the most common one. However, this does not take into account the patent of various types of energy and energy resources, since the enthalpy method is based only on the first law of thermodynamics [1, 2].

The valid value of energy and resources can be provided by an exergy method that takes into account the quality of energy and its ability to transform under the conditions of functioning of the studied object [3, 4].

The works of the following authors: D.P. Gokhshtein, V.M. Brodyansky, Y. Shargut, R. Petela, B.S. Sazhina, A.P. Bulekova, A.I. Andryushchenko, Y.M. Rubinstein, M.I. Shchepetilnikova, and others were the theoretical foundation basis of exergy analysis.

Recently, many researchers have focused on exergy analysis of thermal power plants to optimize energy quality.

A.B. Bogdanov in proves [5] that the application of the concepts of exergy and energy allows the classification of the quality of heat and electric energy.

G. Tsatsaronis and P. Moung-Ho [6] were the first to develop the concepts of preventable and inevitable destruction of exergy, which were used to determine the potential for improving the thermodynamic characteristics and economic efficiency of the system.

Many modern scientists consider thermodynamic processes using exergy analysis. They get good results [7, 8].

The theoretical foundations in the field of integration of thermal processes and pinch analysis are presented in the works of B. Lynnhoff, J. Klemesh, L.L. Tovazhnyansky, R. Smith, L.M. Ulieva, P.A., Kapustenko, etc.

To solve the issue of the effectiveness of technical systems, first of all, the issues of thermodynamic optimization of processes occurring in the elements of heat power equipment and in the heat power systems themselves are considered. One of the most effective methods for parametric optimization of heat and power processes is a pinch analysis or a method for integrating thermal processes [9, 10]. One of the main limitations of this method is its orientation toward the enthalpy approach to the analysis and optimization of heat fluxes in the system under consideration.

Jouan Rashidi and D.S. Agapov investigated systems by exergy analysis and pinch analysis [11, 12]. But no one has yet tried to combine these two methods into one.

Thus, it is necessary to develop a method that combines the advantages of the exergy method and the pinch method.

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Exergy pinch analysis of the boiler

In the theory of pinch analysis, all heat flows can be divided into two groups. The first group is the flows which require cooling. They are called «Hot streams». The second one is the flows which require heating before further work with them. They are called «Cold streams» [9].

The change in the enthalpy of the flow at various initial and final temperatures is expressed by the formula:

$$dH = C_p \cdot M \cdot dT, \qquad (1)$$

where C_p is the specific heat of the flow, J/(kg·K); M is the mass flow rate of the substance flow, kg/s; T is the temperature, K; H is the flow enthalpy, W.

We carry out an exergy analysis of the direct-flow boiler PP-2650-255 GM using the Pinch method.

The direct-flow boiler PP-2650-255 GM is used at powerful thermal power plants in Russia (Surgutskaya GRES-2, etc.), so we will take this boiler as an example for exergy analysis using the Pinch method.

We analyze heat flows in all elements of the boiler unit: economizer, firebox, convection shaft, convective superheater, secondary superheater, air heater, screen superheater, bypass, discharge and hanging pipes.

In calculations and graphs, instead of flow enthalpy, we will use flow exergy. In our case, we will consider the flue gases that give off heat to be «Hot Streams». The second group of streams will include those streams that need to be heated – «Cold Streams». In this boiler unit, «Cold Streams» is water in the economizer, water in hanging pipes, steam in the walls of the furnace and hearth, heating air from the air heater, etc. Thus, in the boiler unit there are 13 hot streams, and 14 cold streams. The data for 27 streams are presented in the table 1.

Table 1. *Boiler parameters*
Таблица 1. *Параметры котла*

Heat flows Тепловые потоки	Initial temperature Температура начальная, °C	Final temperature Температура конечная, °C	Mass flow kg/s Массовый расход, кг/с	Specific heat, kJ/kg K Удельная теплоемкость, кДж/кг К	Flow exergy, MW Эксергия потока, МВт
Flue gas in the economizer Уходящие газы в экономайзере	523	391	760	1,2	71,93
Water in the economizer/Вода в экономайзере	273	315	686	5,06	–70,42
Flue gas in hanging pipes Уходящие газы в подвесных трубах	816	523	760	1,2	183,47
Water in hanging pipes/Вода в подвесных трубах	315	320	686	5,43	–9,39
Flue gases in the walls of the furnace wall and the horizontal flue/Уходящие газы в экранах стен топки и пода горизонтального газохода	2100	1361	760	1,2	574,26
Water evaporation/Испарение воды	320	320	686		–367,87
Steam in the walls of the furnace and the bottom of the horizontal flue/Пар в экранах стен топки и пода горизонтального газохода	320	420	686	7,84	–292,40
Flue gases in the screens of the ceiling of the furnace, horizontal duct, rotary chamber Уходящие газы в экранах потолка топки, горизонтального газохода, поворотной камеры	1361	1324	760	1,2	27,62
Steam in the screens of the ceiling of the furnace, horizontal flue, rotary chamber Пар в экранах потолка топки, горизонтального газохода, поворотной камеры	420	440	206	8,38	–20,14
Flue gases in the screens of a horizontal duct, convection shaft/Уходящие газы в экранах горизонтального газохода, конвективной шахты	1324	1311	760	1,2	9,67
Steam in screens of horizontal flue, convection shaft Пар в экранах горизонтального газохода, конвективной шахты	424	427	686	8,32	–9,95
Flue gas in the screen/Уходящие газы в ширме	1311	1176	760	1,2	99,32
Steam in the screen/Пар в ширме	417	448	722	7,75	–101,44
Flue gases in the inlet stage of the convective superheater/Уходящие газы во входной ступени конвективного пароперегревателя	1176	1059	760	1,2	84,21
Steam in the inlet stage of the convective superheater Пар во входной ступени конвективного пароперегревателя	448	488	722	4,86	–97,69
Flue gases in the outlet stage of a convective superheater/Уходящие газы в выходной ступени конвективного пароперегревателя	1059	899	760	1,2	111,72
Steam in the output stage of the convective superheater/Пар в выходной ступени конвективного пароперегревателя	479	545	736	3,8	–115,85
Flue gases in the control stage of the secondary superheater/Уходящие газы в регулирующей ступени вторичного пароперегревателя	592	523	760	1,2	40,71
Steam in the control stage of the secondary superheater/Пар в регулирующей ступени вторичного пароперегревателя	291	504	127	2,6	–39,65

Table 1

Окончание табл. 1

Flue gases in the intermediate stage of the secondary superheater/Уходящие газы в промежуточной ступени вторичного пароперегревателя	767	592	760	1,2	110,37
Steam in the intermediate stage of the secondary superheater/Пар в промежуточной ступени вторичного пароперегревателя	386	455	600	2,4	–58,15
Flue gas in the exhaust pipes Уходящие газы в отводящих трубах	816	767	760	1,2	32,39
Steam in the exhaust pipes/Пар в отводящих трубах	455	478	600	2,2	–19,02
Flue gases in the outlet stage of the secondary superheater/Уходящие газы в выходной ступени вторичного пароперегревателя	899	816	760	1,2	56,07
Steam in the outlet stage of the secondary superheater Пар в выходной ступени вторичного пароперегревателя	478	545	600	2,2	–57,29
Flue gas in the air heater/Уходящие газы в воздухоподогревателе	391	127	760	1,16	101,83
Air in heater/Воздух в воздухоподогревателе	50	339	350	1,02	–36,32
				Hot streams gave Горячие потоки отдали	1503,57
				Cold streams took Холодные потоки приняли	–1295,57

The dependence of the exergy function Ex on the amount of heat is calculated by the formula:

$$Ex = m \cdot e, \tag{2}$$

where m is the mass flow rate of the substance flow, kg/s; e is the specific exergy, J/kg.

Specific exergy for a stream that has a final and initial temperature is determined by the formula [12]:

$$e = c_p \cdot \left[T_1 - T_2 - T_0 \cdot \ln \frac{T_1}{T_2} \right], \tag{3}$$

where c_p is the specific heat of the flow, J/(kg·K); T_1 is the initial temperature, K; T_2 is the final temperature, K; T_0 is the ambient temperature, K.

Formula (3) is valid for continuous and stationary processes, as well as for processes without phase transitions.

It is also possible to determine the exergy of flows using the device [14]. The device displays the exergy values on the display. This device allows you to avoid errors in data collection and calculations.

Steam at different temperatures has different specific isobaric heat capacity.

Specific heat capacities of steam and water are determined according to the table at a given temperature and pressure.

The average specific heat capacity of a substance is defined as:

$$\overline{c_p} = \frac{c_{pt2} + c_{pt1}}{2}, \tag{4}$$

where c_{pt1} and c_{pt2} are standard specific isobar heat capacities of a substance at temperatures t_1 and t_2, respectively.

The data are presented in table 2.

We determine the exergy for the flue gases in the economizer («Hot stream 1») by the formula (2), (3). We take the ambient temperature equal to 0 °C.

$$E_{h1} = 1,2 \frac{kJ}{kg \cdot °C} \cdot 760 \frac{kg}{c} \times$$

$$\times \left[796K - 664K - 273K \cdot ln \frac{796K}{664K} \right] = 71,93MW.$$

Then we determine the exergy that the water received in the economizer – «Cold Stream 1»:

$$E_{c1} = 5,06 \frac{kJ}{kg \cdot °C} \cdot 686 \frac{kg}{c} \times$$

$$\times \left[546K - 588K - 273K \cdot ln \frac{546K}{588K} \right] = -70,41MW.$$

In this way, we determine the exergy for all elements of the boiler unit, except the exergy for the screen of the furnace walls and the bottom of the horizontal gas duct. This is due to the fact that the exergy of the exhaust gases in this element is spent not only on heating, but also on water evaporation.

We give a calculation of this element in more details. To begin with we need to determine the exergy that the exhaust gases give off in the walls of the furnace and the horizontal gas duct (from 2100 to 1361 °C, «Hot Stream 3»). We use formulas (2), (3)

$$E_{h3} = 1,2 \frac{kJ}{kg \cdot °C} \cdot 760 \frac{kg}{c} \times$$

$$\times \left[2373K - 1634K - 273K \cdot ln \frac{2373K}{1634K} \right] = 574,26MW.$$

There are two processes in the furnace:

1) water turns into steam;

2) steam heats up.

Therefore, we will use two types of exergy.

During evaporation or condensation, as well as melting or crystallization from the melt, which occur at a constant ambient temperature, the thermal specific exergy is [15]:

$$e_f = \Delta h \cdot \left(1 - \frac{T_0}{T} \right), \tag{5}$$

where Δh is the increment of enthalpy.

Table 2. *Specific heat capacity of water and steam for flows*
Таблица 2. *Удельная теплоемкость воды и пара для потоков*

Heat flows Тепловые потоки	Temperature Температура, °С		Pressure, MPa Давление, МПа		Specific heat Удельная теплоемкость		
	Initial Начальная	Final Конечная	Initial Начальное	Final Конечное	Initial Начальная	Final Конечная	Average Средняя
Water in the economizer Вода в экономайзере	273	315	31	30,5	4,77	5,351	5,06
Water in hanging pipes Вода в подвесных трубах	315	320	30,5	28,5	5,351	5,512	5,43
Steam in the walls of the furnace and the bottom of the horizontal flue Пар в экранах стен топки и пода горизонтального газохода	320	420	28,5	28	5,512	10,176	7,84
Steam in the walls of the furnace and the bottom of the horizontal flue Пар в экранах стен топки и пода горизонтального газохода	420	440	28	27,6	10,176	6,589	8,38
Steam screens of horizontal flue, convection shaft Пар экранах горизонтального газохода, конвективной шахты	424	427	27,6	27	8,828	7,826	8,327
Steam in the screen Пар в ширме	417	448	27	26,5	9,908	5,596	7,75
Steam in the inlet stage of the convective superheater Пар во входной ступени конвективного пароперегревателя	448	488	26,5	26,2	5,596	4,118	4,857
Steam in the output stage of the convective superheater Пар в выходной ступени конвективного пароперегревателя	479	545	26,2	25,5	4,313	3,3	3,8
Steam in the control stage of the secondary superheater Пар в регулирующей ступени вторичного пароперегревателя	291	504	3,9	3,86	2,962	2,279	2,62
Steam in the intermediate stage of the secondary superheater Пар в промежуточной ступени вторичного пароперегревателя	386	455	3,86	3,71	2,58	2,287	2,43
Steam in the exhaust pipes Пар в отводящих трубах	455	478	3,71	3,7	2,287	2,278	2,28
Steam in the outlet stage of the secondary superheater Пар в выходной ступени вторичного пароперегревателя	478	545	3,7	3,65	2,278	2,273	2,27

In the theory of pinch analysis, the flow enthalpy is expressed in MW, since the mass flow rate (kg/s) is used in the calculations, this can be seen from formula (1). Therefore, in our calculations, the exergy is expressed in MW.

The full exergy of evaporation («Cold Stream 3») is determined by the formulas (2), (5):

$$E_{c3} = 686\frac{kg}{c}\cdot\left(1400\frac{kJ}{kg} - 2500\frac{kJ}{kg}\right)\times$$
$$\times\left(1-\frac{273K}{593K}\right) = -367,87\ MW.$$

In order to determine the exergy of steam, it is necessary to know the average specific heat (the data are presented in table 2). According to the table, we determine the specific heat capacity of the steam in the furnace at the initial and final temperature and find the average by the formula (4):

$$\overline{c_p} = \frac{5,512+10,176}{2} = 7,84\frac{kJ}{kg\cdot{}^\circ C}.$$

When heating steam ("Cold Stream 4») we use the thermal component of exergy, which is found by the formulas (2), (3):

$$E_{c4} = 7,84\frac{kJ}{kg\cdot{}^\circ C}\cdot 686\frac{kg}{c}\times$$
$$\times\left[593K - 693K - 273K\cdot ln\frac{593K}{693K}\right] = -293,40MW.$$

Then the remaining flows are calculated by the formulas (2), (3), the calculated data are taken from table 1.

In the calculations, we take into account the cooling of flows using bypass 1, bypass 2, bypass 3 and the cooling of the secondary steam using bypass 4.

According to the theory of pinch analysis, external energy sources are called external utilities. Energy carriers supplying energy to the system, such as steam, burning gas, etc., are called hot utilities, and energy carriers that divert energy from processes – cooling water, etc., are called cold utilities [9]. In our case, bypass is a cold utility.

We calculate the amount of exergy that the bypass receives from steam according to the formulas (2), (3). The calculated data are presented in table 3.

Table 3. *Bypass specifications*
Таблица 3. *Характеристики байпаса*

Bypass Байпас	Temperature Температура, °С		Mass flow kg/s Массовый расход, кг/с	Specific heat, kJ/kg K Удельная теплоемкость, кДж/кг К	Exergy, MW Эксергия, МВт
	Initial Начальная	Final Конечная			
1	427	417	36	4,2	0,87
2	488	479	14	4,2	0,32
3	440	424	480	4,2	18,85
4	504	386	478	4,2	140,01
				Total: Итого:	160,05

We convert heat flows into a hot composite curve and a cold composite curve according to the theory of pinch analysis. Composite curves in the exergy – temperature coordinate system, are shown in Fig. 1.

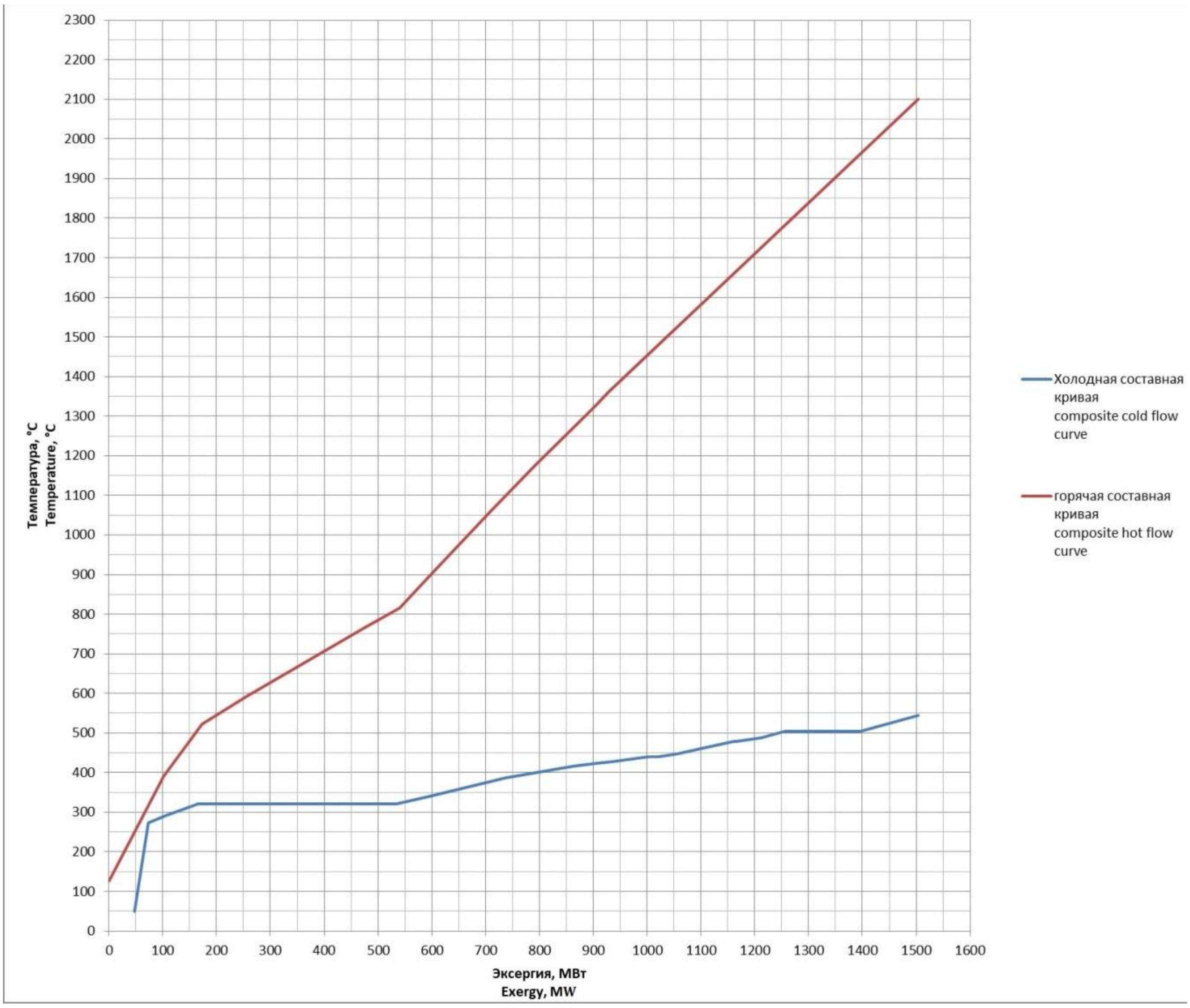

Figure. *Compound curves in the exergy–temperature coordinate system*
Рисунок. *Составные кривые в системе координат эксергия–температура*

The projections of the curves onto the exergy axis overlap. This means that the heat removed from the hot composite curve (set of hot streams) can be used to heat the cold composite curve (set of cold streams) by arranging heat transfer between the streams [16, 17].

According to the theory of pinch analysis, each of the composite curves has a section which projection onto the abscissa axis does not overlap with the projection of another curve. This means that in its upper part the cold composite curve requires an external heat source (power $Q_{H,\,min}$), and the hot composite curve in its lower part needs an external heat source ($Q_{C\ power,\,min}$). These values represent the theoretical needs for hot and cold energy [16, 18, 19].

Results and discussions

Analyzing the Figure, we conclude that 47,9 MW of unused exergy remains at the bottom of the graph. Thus, we can optimize the boiler unit using these 47,9 MW exergy. Below the pinch point, the cold flow is air in the air heater; therefore, to optimize thermal processes, the heating surface area of the air heater can be increased.

The exergy method also determines the need to take into account the fuel exergy of the boiler unit.

Most of the fuel exergy is chemical exergy. Z. Rant defined a formula for calculating specific fuel exergy [20, 21]:

For liquid fuel:

$$e_0 = 0,975 \cdot Q_h \ , \qquad (6)$$

where Q_h is the higher calorific value of fuel.

The formula (6) is valid if the molecule contains more than one carbon atom. The formula (6) is not suitable if there is a noticeable amount of methane, hydrogen and carbon monoxide in the gases.

We calculate the fuel exergy for the selected boiler according to the formulas (2), (6). Fuel is fuel oil with a higher calorific value Q_h = 42,98 *MJ*, the flow rate is 51 kg/s.

$$E_{\text{fuel}} = 51\frac{kg}{s} \cdot 0,975 \cdot 42,98MJ = 2135,7\ MW.$$

The boiler received 2135,7 MW of fuel exergy, but hot flows gave 1503,37 MW of exergy. Therefore, the loss of fuel exergy is 29 %. This makes it necessary to find ways to reduce the loss of fuel exergy in a given type of heat power equipment and a specific boiler unit.

Conclusion

Exergy pinch analysis allows identifying unused exergy and determining in which part of boiler the loss occurs. According to the calculations and the graph, it can be seen that the hot flows gave 1503,57 MW of exergy, the cold flows took 1295,57 MW of exergy, taking into account the cooling of the working fluid bypass with 160,05 MW of exergy. Thus, 47,9 MW of unused exergy was found in this boiler unit. It was also determined from the graph that below the pinch point, the cold flow is air in the air heater; therefore, from the point of view of optimizing thermal processes, the heating surface area of the air heater can be increased. In support of this fact, it was revealed that the lowest exergy efficiency of the heat exchangers of the boiler is the efficiency of the air heater, which is 35,7 %. The solution of design problems to determine the surface area of the heating of the air heater does not cause fundamental difficulties.

It should be noted that the proposed method of exergy Pinch analysis is focused on the environment, i. e. takes into account the operating conditions of technological equipment (ambient temperature) [22, 23]. It can be useful for equipment which effectiveness directly depends on environmental parameters (for example, gas turbine plants).

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ЭКСЕРГЕТИЧЕСКИЙ ПИНЧ-АНАЛИЗ ВСЕХ ЭЛЕМЕНТОВ КОТЕЛЬНОГО АГРЕГАТА И КОТЕЛЬНОГО АГРЕГАТА В ЦЕЛОМ

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Актуальность *исследования обусловлена необходимостью повышения энергоэффективности теплотехнических систем, так как все виды топлива дорожают. В этой связи возникает необходимость создания метода термодинамического усовершенствования теплотехнических систем.*
Цель: *создание метода усовершенствования теплотехнических систем, применение данного метода на примере котельного агрегата ПП-2650-255 ГМ.*
Объекты *прямоточный котел ПП-2650-255 ГМ, для которого производится термодинамический анализ процессов, протекающих в отдельных элементах котла –воздухоподогревателе, экономайзере, топке, пароперегревателе. Проводится анализ всех тепловых потоков на каждом элементе котла.*
Методы. *В качестве инструмента исследования использован эксергетический метод термодинамического анализа, позволяющий учитывать потенциал энергии (качественные характеристики) тепловых процессов. На сегодняшний день наиболее эффективным методом параметрической оптимизации теплоэнергетических процессов является метод интеграции тепловых потоков (пинч-метод). Однако пинч-метод основан на изменение энтальпии, которая не учитывает качественные характеристики энергии. В статье продолжается развитие пинч-метода, вместо энтальпии используется эксергия. Оптимизация теплотехнических параметров производится путем использования эксергетического пинч-метода.*
Результаты*. Эксергетический пинч-анализ позволяет выявить неиспользуемую эксергию и определить, в какой части котельного агрегата происходят потери. По расчетам и графику видно, что горячие потоки отдали 1503,57 МВт эксергии, холодные потоки приняли 1295,57 МВт эксергии с учетом охлаждения рабочего тела байпасом. Таким образом, в данном котлоагрегате обнаружилось 47,9 МВт неиспользуемой эксергии. Результаты эксергетического пинч-анализа позволяют сформулировать и обосновать конкретные конструктивные меры по повышению энергоэффективности котельного агрегата. Данный анализ позволяет эффективно использовать энергию и ресурсы теплотехнического оборудования.*

Ключевые слова:
Энергоэффективность, эксергия, эксергетический анализ, тепловой баланс, эксергетический баланс, пинч-анализ.

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