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IMPROVING THE PERFORMANCE OF BOILER PLANTS DUE TO THE USE OF DIRECT AND REVERSE RANKIN CYCLES

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Abstract. To generate electricity from biofuels at heat and power enterprises of Ukraine, the direct Rankine cycle is used, which ensures the efficiency of energy transformation within η = 0.25-0.55. To improve the efficiency of fuel energy, use in boiler plants, it is also proposed to implement a reverse Rankine cycle scheme. Such a proposal is good to use in enterprises where there is a need for drying biomaterials. Instead of a separate boiler for drying processes, it is proposed to use the energy of water condensation from flue gases. In this case, the cost of electricity for the operation of the compressor is significantly less than the amount of heat obtained by condensing water from flue gases. The efficiency coefficient or COP of the reverse Rankine cycle can have values greater than one η = COP > 3. The combination of direct and reverse Rankine cycles in the technological scheme of the boiler plant increases the efficiency of using primary energy sources.

The paper analyzes the representation of energy as a combination of two components: the potential *P* and the dynamics *D*. The Leibniz model, in which the power *N* is represented as the product of the potential *P* and the dynamics *D* with the unification of the unit of measure Watt, allows calculating the efficiency of transformation processes of different types of energy. To improve the energy performance of boiler plants, further development of the Newton model is proposed, which makes it possible to calculate the process dynamism indicator – μ. In Newton's model, within the framework of one type of energy, the dynamism indicator is calculated – as the ratio of dynamics to the initial potential $\mu = D / P$. Dynamism □ can be calculated as the reciprocal of the resistance R, provided that the units of measurement of the energy components – potential and dynamics are unified. To increase the efficiency of biofuel combustion energy use, the idea of the reverse Rankine cycle has been implemented. The moisture condensation temperature of the flue gases increases due to an increase in the pressure of the medium. To do this, the smoke exhauster is moved from the discharge zone to the pressure zone. The additional energy from the flue gases of the boilers can be used to increase the efficiency of drying biomaterials. It is possible to refuse an additional boiler for drying materials, which significantly reduces fuel costs, and also improves the environmental performance of technological processes.

Key words: energy, Rankine cycle, efficiency, biomass, drying.

Introduction. Heat supply systems of Ukrainian cities are combined into large energy complexes – district heating systems (DH). For the past few decades, DH systems have been operating stably, so only routine measures have been taken. Several pressing issues can be identified. First of all, this is the physical and moral aging of power equipment, as well as a decrease in efficiency and other indicators of energy excellence.

Analysis of recent research. The Millennium Declaration on sustainable development noted the requirement to double the global rate of increase in efficiency by 2030 [1, 2]. Energy contributes about 60% of total global greenhouse gas emissions. Therefore, in order to improve the environmental situation, the use of biomass as a remnant of the processing of agricultural products as fuel is encouraged. Biofuel contains less ash and provides a significant improvement in the environmental performance of power equipment [3]. A positive factor is the development of various kinds of models aimed at improving the energy performance of both the main and auxiliary equipment [4, 5]. Modeling of energy processes makes it possible to predict and analyze economic, environmental and other performance indicators of various technologies [6-8].

An analysis of trends in the development of world energy has shown that the main thing is to extend the life of energy enterprises and equipment by improving performance [9]. First of all, this is the development and improvement of the performance of the joint generation of heat and electricity at urban CHPPs with steam boilers, as well as the transfer of heating boiler plants to the steam mode of cogeneration of electricity and heat. In addition, steam boiler plants of type D, E, K, etc., which are many in the processing industry, can be transferred to cogeneration mode with the combustion of biofuels (sunflower husks, miscanthus, energy willow) and other energy fuels in Ukraine (Table 1).

Table 1 – Characteristics of different types of fuel

Characteristics	Units Measure-ments	Sunflower husk	Miscanthus	Stone charcoal	Wood
Calorific value	MJ/kg	19-20	18.9	18-23	18-19.5
Ash content	%	2.7-4.5	4.88	20	0.5-1.5
Humidity	%	6-8	10	5-6	7-8
Sulfur	%	0.23-0.45	0	5-5	0

The selected set of problems involves the development of goals and objectives aimed at improving the performance of the energy industry, especially for the rational and sustainable development of cities.

The Purpose of research. Analysis of the problems of development of heat supply systems for settlements, development of measures to improve the quality indicators of the operation of the main and auxiliary equipment, the use of energy fuels with improved characteristics.

To solve the problem, the research **tasks** are defined:

– analysis of indicators of perfection of energy processes to increase the capacity of equipment and systems;

– development of indicators characterizing the dynamic processes of hydro and aero systems;

– search for effective methods of using energy fuel and new technologies that improve the performance of its use.

Materials and research methodology. Two options for organizing energy processes – direct and reverse Rankine cycles – were used in the research. Features of the organization of the reverse cycle significantly increase the energy value of low-potential flue gases due to an increase in pressure and, as a result, an increase in the temperature of the phase transition – moisture condensation. When designing the channels of the recuperators, indicators of energy perfection were used. In addition to the well-known indicators of the efficiency of transformation of different types of energy, an indicator of the dynamism of the implementation of potentials into work is proposed.

Research results. Indicators of the perfection of energy processes are used in solving problems of increasing the power of equipment and systems. First of all, it is necessary to analyze the concept of energy E, which can be attributed to different types of manifestation (electricity, heat, aero and hydro dynamics ...). Dynamics is inherent in energy – movement, as well as transformation from one type to another. In engineering, energy is most often associated with work *A*. The unit of measure for work is Joule [J], which is calculated as the product of force *F* or weight *G* and the travel path *l*.

$$E \equiv A = F \times l = G \times l, \quad [n] \times [m] = [J]. \tag{1}$$

An important indicator of energy is power, which characterizes the intensity of work. The formulas for calculating the power N are similar in different manifestations of energy [10]. Aristotle proposed the concept of energy as a combination of two components: potential P and dynamics D [11], but the parameters are formed into groups according to different measurable indicators:

Hydraulic energy $N_{hy} = \rho gQH,$ [W]; (2)

Electric energy $N_{el} = U \times I,$ [W]; (3)

Thermal energy $N_t = c\Delta T\, M = \Delta i \times M,$ [Вт]. (4)

In hydraulics, parameter groups are formed based on the flow rate:

Q [m^3/s] – volumetric; ρQ [kg/s] – mass; ρgQ [n/s] – weight flow rate.

In electricity, the power formula can be unambiguously divided into two components: voltage U – potential and current strength I – dynamics. In thermal energy, the potential is represented by enthalpy i, however, when calculating heat transfer processes or heat dynamics, the potential should be the temperature T, since the movement or dynamics of heat goes from a high temperature to a lower one. It is more logical to combine heat capacity c with mass to represent the amount of heat in the considered body mass M, but such a statement requires investigation. Most importantly, power is the only indicator for which the unit of measurement [W] is unified, which makes it possible to determine the efficiency of transformation of different types of energy.

$$\text{Efficiency}_{\text{pump}} \equiv \eta_{\text{pump}} = N_{hy} / N_{el}, \quad [W]/[W]. \quad (5)$$

The energy that we expend in the pumping unit is converted into useful work for lifting and moving water. A few decades ago, power could be represented in [hp], that is, one horsepower is equivalent to 1h.p. = 785W.

Newton formulated a model for the correspondence of dynamic processes to the initial potential $D \equiv P$, taking into account the resistances in the system R.

Hydraulic energy $Q \equiv H^{0,5}/(R_{hy}+ \alpha)^{0,5};$ (6)

Electric energy $I = U / R_{el};$ (7)

Thermal energy $q \equiv \Delta T / R_t.$ (8)

But, only for electricity, the formula uses the equal sign, where the current strength I and potential U are linearly correlated using the proportionality coefficient or resistance R. The value of the above formulas would be significantly higher if, within the unified power indicator, the dynamics and potential indicators were unified [12]. You can enter a normalized indicator of process dynamism.

$$\mu_{el} = D / P = 1/ R \quad \text{– for electricity;} \quad (9)$$

$$\mu_{hydr} = D / P = 1 / (R + \alpha) \quad \text{– for hydrodynamics.} \quad (10)$$

Leibniz formulated the concept of power $N = P \times D$ as the product of the potential P and the dynamics of D. Due to the unification of the units of power in W, the transformation coefficient of different types of energy is presented in a normalized form$0 < \eta < 1$. The Leibniz power model is good to use optimization of processes in order to ensure minimum costs. Thus, the values $\eta > 0.8$ have already been reached in pumps, fans or smoke exhausters. Technologies for generating electricity at thermal and nuclear power plants, which theoretically represent the direct Rankine cycle, have an efficiency range of $\eta = 0.25\text{-}0.45$.

Recently, heat generation technologies based on the reverse Rankine cycle have become widespread. Such technologies use phase transition processes, when the working fluid in the rarefaction zone changes from a liquid state to a gaseous state with the absorption of a large amount of energy at a lower temperature – cooling and vice versa, condensation in a high pressure zone releases a comparable amount of heat when the gas turns into a liquid.

Under favorable conditions (when the value of the compressor capacity and a small increase in the switching efficiency increase temperature), the efficiency coefficient COP is observed as the use of the energy of the consumed energy to the heat received from the flue gas water condensation can be greater than the consumption of COP > 5. The technology can be designated as a system with the definition of energy balance, since for 1 kW of energy expended, more than 5 kW is generated at a higher temperature than at the source. This performance is called a pump, since energy is used from a cold environment to a warmer one. On Fig. 1 shows a diagram and graphs of the processes of the reverse Rankine cycle in a heat pump.

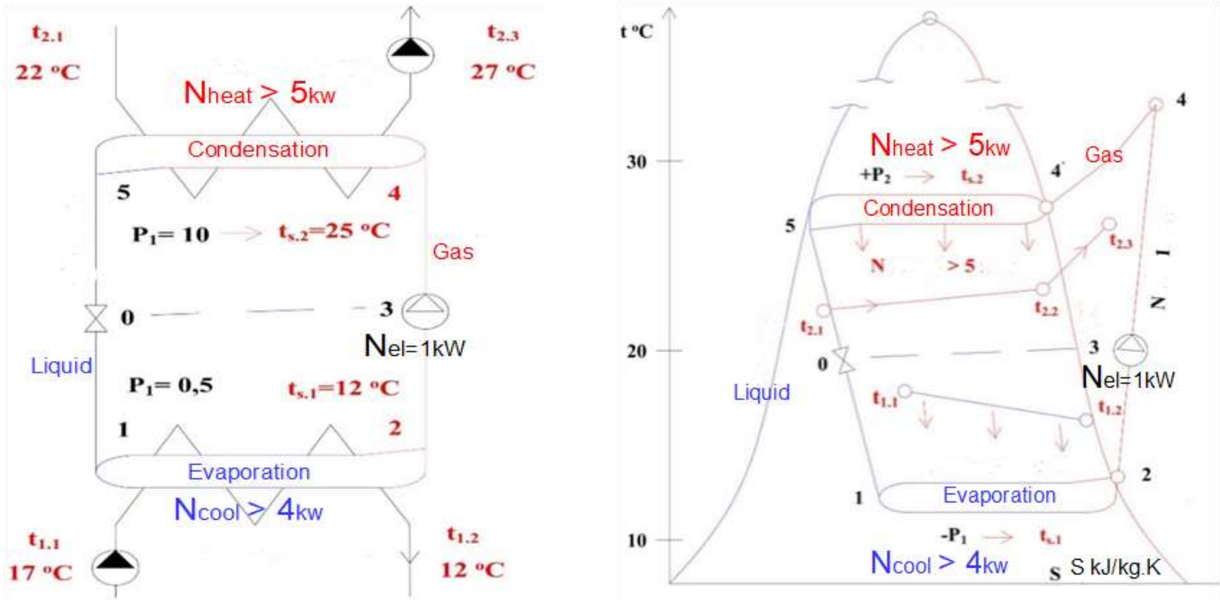

Fig. 1. Representation of reverse Rankine cycle processes:
a – scheme of heat pump processes; b – parameters of the heat pump

The main function of the processes of the reverse Rankine cycle is the extraction of energy from low potential sources (with a low temperature) and the transfer of this energy to a medium with a high potential (with a higher temperature). The conditional axis of separation of parameters in the system can be considered the line 0-3 between the regulator and the compressor. Under natural conditions, the liquid phase of the coolant medium is always at the bottom, and the gaseous phase is located above the liquids. The heat pump circuit can be divided into two parts.

Point 0 indicates the regulator. The parameters behind the regulator can be considered the beginning of the cycle. Section 1-2 is responsible for the transfer of energy from a conditionally cold source – the external environment to the evaporator, in which a phase transition from a liquid to a gaseous state occurs. The cooling power N_{cold} is significantly greater than the electric power $N_{el\ spent}$ on the compressor. COP in the cooling zone could be Section 4-5 is responsible for the transfer of energy from the capacitor of a conditionally hot source to the external environment. The capacitor undergoes a phase transition from the gaseous state to the liquid phase. Thus, the condenser heats the environment, and the heating power N_{heat} can be significantly greater than the electric power $N_{el\ spent}$ on the compressor.

COP is the coefficient of transformation of different types of energy: electricity N_{el} is consumed, and thermal power N_{heat} is useful. In a normalized form, with a small temperature difference, the energy transformation efficiency can be greater than unity $\eta > 1$. The law of conservation of energy is not violated, since in the technological cycle how much energy is extracted in the lower part, the same amount of energy (but taking into account dissipation) is given off in the upper part. The electrical energy in the heat pump is spent on the formation of pressure and vacuum, as well as on transport with its own values of losses and, accordingly, efficiency. And heat and cold are obtained by organizing natural processes in accordance with their separate balance ratios, which are balanced taking into account dissipation and have their own efficiency values. Rankine's ideas, implemented in the form of cyclic processes, can also be organized in technologies that require heating with a large amount of energy for drying biomaterials: soybeans, wheat, etc.

To increase the efficiency of such processes, it is necessary to distinguish between changes in parameters within one type of energy [12]:

1 – Change in temperature (potential). To heat 1 kg of water by 100°C, it is necessary to spend 400 kJ of energy.

2 – The change in thermal energy during a phase transition occurs at a constant temperature, but has a much larger range of energy changes. When converting 1 kg of steam into water, 2000 kJ can be obtained at a constant temperature t_s = 100°C. Therefore, if you need to heat any medium, it is better to do it due to the energy of the phase transition and better due to the condensation of the vapor part of the flue gases. On Fig. 2 shows a diagram of power equipment, including a boiler for generating saturated steam and a drying plant with auxiliary equipment.

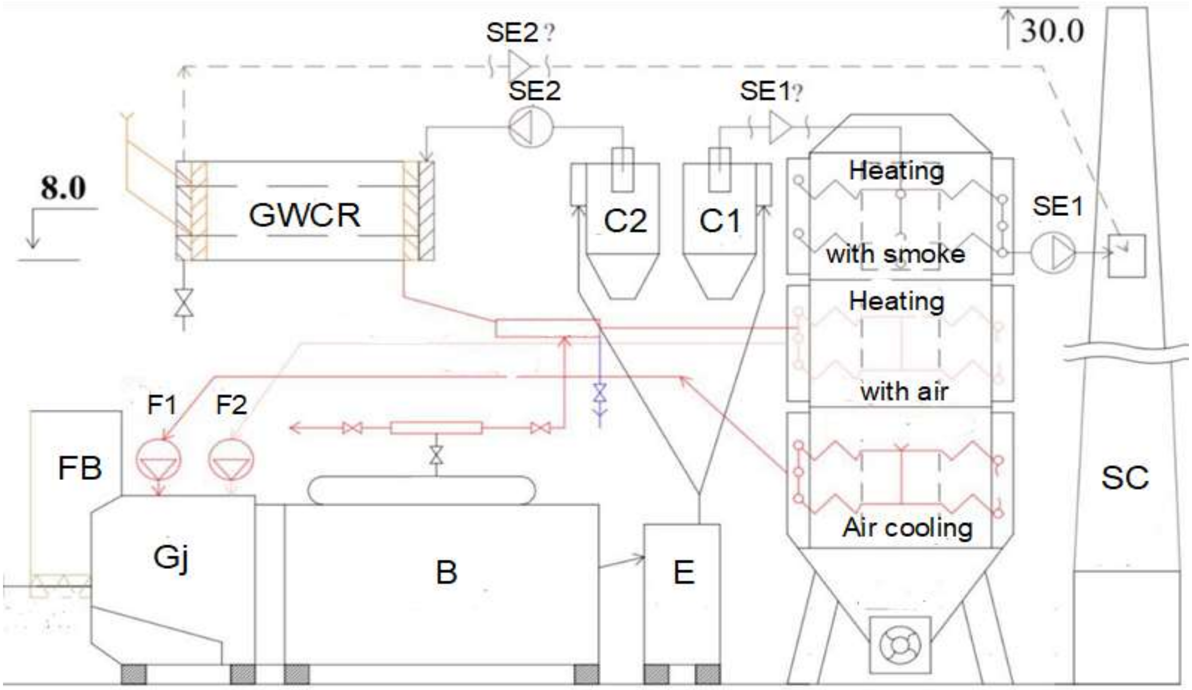

Fig. 2. Scheme of power equipment of the system for drying biomaterials:
FB – fuel box; Gj – gas-jet; B – Boiler; E – economizer; C – cyclone; GWCR – flue gas water condensation recuperates; Fan; SE – smoke exhauster; SC – smoke chimney

To organize the process of drying or removing moisture from biomaterials, dry heated air or flue gases are used. To heat the air, you can use electricity, the energy of burning fuel. However, a more economical option for air heating can be considered the energy of flue gases after boilers, the temperature of which is often more than 150°C. As an innovative increase in the temperature of water vapor condensation, it is proposed to use a flue gas water condensation recuperate GWCR – a flue gas air heater.

In the first part of the dryer, preheating of soybeans is formed with the transfer of part of the moisture from soybeans to flue gases. To organize the soybean heating process, it is necessary to transfer energy from the flue gases without condensation, since condensation will lead to the transfer of a large amount of water to the soybean, which is contrary to the task of drying. To eliminate condensation, it is advisable to place the smoke exhauster *D1* between the dryer and the chimney to form a vacuum in the first part of the dryer. The temperature of the phase transition of water in the flue gases is reduced, which eliminates the occurrence of moisture condensation in the flue gases.

In the second part of the dryer, the task is to transfer more heat to dry air. Analysis of parameter changes in Fig. 3 shows that an obstacle to the transfer of energy of the phase transition is an insufficient potential – the temperature of the phase transition. Therefore, for the second part of the dryer, it is necessary to solve the problem of improving the parameters of the recuperator based on optimizing the value of the potential – pressure [13]. The problem of increasing the moisture condensation temperature of flue gases can be solved by changing the installation location of the smoke exhauster *D2* in order to organize pressure in the heat exchanger in the flue gas channels.

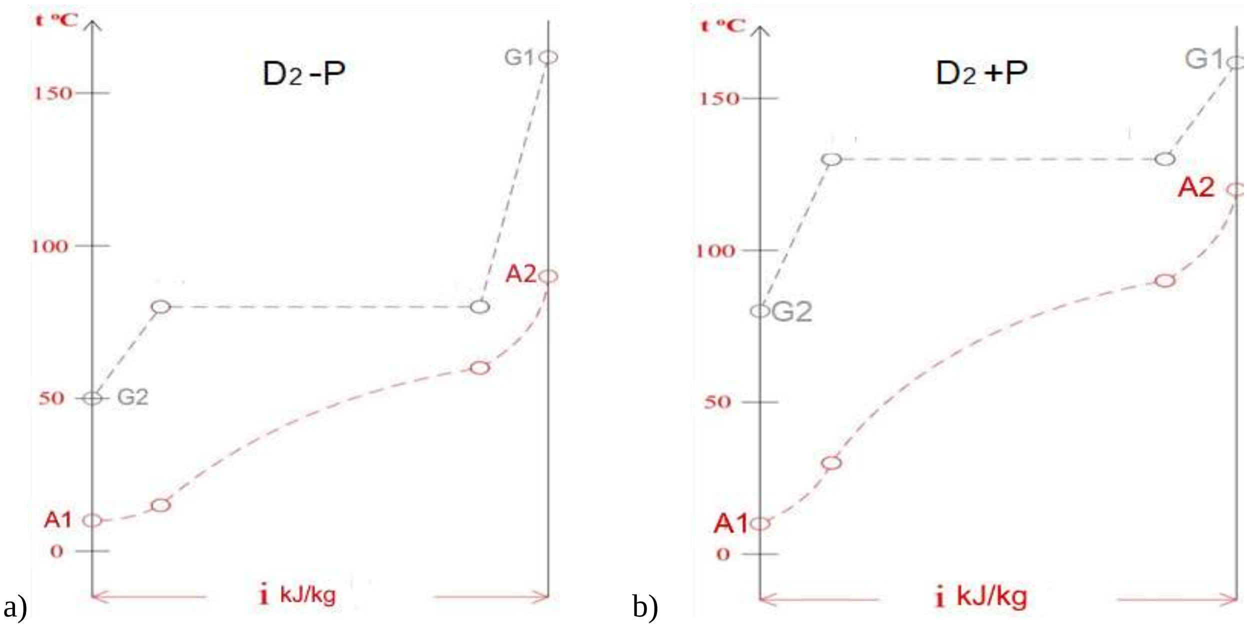

Fig. 3. Heat exchange in the heat exchanger at different potentials in the gas channels:
a – rarefaction in gas channels; b – pressure in gas channels

The most economical and environmentally friendly stage of soybean dehydration is cooling in the third section. In the cooling zone, an important parameter is the degree of air dryness d_{airB1} = 5gr/kg.d.m. If the smoke exhauster *D2* is installed after the heat exchanger, and in the flue gas channels, the discharge of moisture condensation occurs at a constant temperature $t_{s.D2-}$ = 85°C = const. The amount of flue gas heat transferred to air heating during condensation will be 5 times greater than when the flue gas temperature decreases.

To improve the efficiency of the drying process of biomaterials, it is proposed to increase the temperature of condensation of moisture from flue gases by increasing the pressure in the flue gas channels and, accordingly, increasing the temperature at which condensation will take place [8, 9]. This solution corresponds to Rankine's idea in the zone of pressure increase in the system by the compressor. To do this, as an innovative solution, it is proposed to install a *D2* smoke exhauster in front of the heat exchanger, that is, switch it to the fan or compressor mode (Fig. 1 and Fig. 2). Changing the potential – pressure in the flue gas channels from discharge to pressure will increase the condensation temperature to $t_{s.D2+}$ = 130°C and higher. To implement such a solution, the *D2* smoke exhauster moves from the zone after the GWCR recuperator to the zone after the Ts2 cyclone, switches to the compressor mode to create the required vacuum.

However, the increase in pressure that the compressor generates can significantly increase the cost of electrical energy for the drive. Therefore, an alternative to increasing the air temperature by increasing the compressor speed can be considered the use of a heater. The heater solves the problem of increasing the air temperature by using steam from the boiler. The heater uses saturated steam, which also condenses at a constant phase transition temperature $t_{s.Steam}$ = 180°C. Thus, the paper formulated the problem of optimizing the parameters of the joint operation of the recuperate and heater. Today, the balance of fuel costs for the operation of a dryer with a supply of 20 tons of soybeans per hour is more than Vu = 500kg.c.t./hour. The innovative method of drying soybeans using flue gas heat recovery for air heating provides fuel costs by more than 50%. The energy costs for the operation of fans and smoke exhausters are not considered, since the costs for the operation of blowers remain comparable.

Conclusions. The possibility of increasing the temperature of the reverse phase transition within the framework of the use of the Rankine cycle makes it possible to obtain significant savings in resources in the system for drying biomaterials due to insignificant energy costs for the compressor, which increases the pressure in the flue gas channels of the recuperator. To implement this idea, the smoke exhauster operating in the boiler plant is switched to the compressor mode (the flue gas channels in the heat exchanger will be under pressure). With a new installation of a smoke exhauster-compressor with pressure in the recuperator, air heating will not exceed $t_{air + P}$ > 120°C due to an increase in the temperature of the phase $t_{sSG + P}$ > 130°C.

To analyze the perfection of energy processes, it is proposed, in addition to the indicator of the conversion efficiency of different types of energy, to apply the indicator of dynamism – as the ratio of the dynamic component of energy to the initial potential. Such a variant of an innovative solution can be qualified as an architecture of energy potentials of various kinds of technological processes.

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ПОЛІПШЕННЯ ПОКАЗНИКІВ РОБОТИ КОТЕЛЬНИХ УСТАНОВОК ЗА РАХУНОК ВИКОРИСТАННЯ ПРЯМОГО І ЗВОРОТНОГО ЦИКЛІВ РЕНКІНА

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Анотація. Для створення електроенергії з біопалива на теплоенергетичних підприємствах України використовується прямий цикл Ренкина, який забезпечує ефективність трансформації енергії в межах η = 0,25 – 0,55. Для підвищення ефективності використання енергії палива в котельних установках запропоновано реалізувати схему зворотного циклу Ренкіна. Таку пропозицію добре використати на підприємствах, де є потреба в осушенні біоматеріалів. Замість окремого котла для осушення пропонується використовувати енергію конденсації води з димових газів. В цьому випадку витрати електрики на роботу компресора істотно менші за кількість тепла, отриманого при конденсації води з димових газів. Коефіцієнт ефективності або *COP* зворотного циклу Ренкина може мати значення більше одиниці $\eta = COP > 3$. Поєднання в технологічній схемі котельної установки прямого та зворотного циклів Ренкіна збільшує ефективність використання первинних джерел енергії.

У роботі виконано аналіз уявлення енергії як поєднання двох компонент: потенціалу *П* і динаміки Д. Модель Лейбніца, у якій потужність N представляють, як добуток потенціалу *П* на динаміку *Д* з уніфікацією одиниці виміру Ватт, дозволяє розраховувати ефективність процесів трансформації різних видів енергії. Для покращення енергетичних показників котелень запропоновано подальший розвиток моделі Ньютона, що дозволяє розраховувати показник динамізм процесів μ. У моделі Ньютона в рамках одного виду енергії розраховується показник динамізму – як відношення динаміки до вихідного потенціалу μ = *Д/П*. Динамізм можна розраховувати як зворотну величину опорів *R* за умови уніфікації одиниць вимірювання компонентів енергії – потенціалу та динаміки.

Показано приклад успішного використання біомаси як основне паливо котельних установок, оскільки містить менше золи. Використання ідеї зворотного циклу Ренкіна про підвищення температури конденсації вологи димових газів за рахунок підвищення тиску середовища забезпечує підвищення системної ефективності процесів. Найкраще використання енергії димових газів котлів підвищує ефективність осушення біоматеріалів, суттєво зменшує витрати енергії, покращує екологічні показники роботи технологічних процесів.

Ключові слова: енергія, цикл Ренкина, ефективність, біоматеріали, осушення.

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