

The object of the study is the energy efficiency of technological systems and complexes of enterprises. The study solved the problem of scientifically based technologies for system analysis and optimization of energy efficiency of multi-purpose systems. It is proved that the traditional definition of energy efficiency fails to identify the fundamental causes of inefficiency and assess the energy efficiency potential of the system. The use of exergy technologies is effective for optimizing heat engines, but for heat technology systems it gives rise to methodological contradictions.

The presented entropic technologies for analyzing and optimizing energy efficiency do not have the indicated disadvantages. By combining entropic characteristics with energy characteristics, the "principle of energy compensation of irreversibility" was formulated, which is the basis of the analysis methodology.

The results of the applied analysis of sugar production, which has an energy generation system and an energy technological complex of complicated configuration, showed the effectiveness of this technology. It was determined that compensation only for the internal irreversibility of the processes of the energy generating system consumes about 55% of the primary energy resource, which can change the classical concept of energy efficiency measures.

The results obtained were made possible by establishing the dependence between the irreversibility of processes, entropy and compensatory energy costs. This allowed to approach the idea of energy efficiency in a new way, prioritizing the qualitative characteristics of processes and focusing on the thermodynamic perfection of systems.

The proposed entropic technologies can be the basis for the formation of a comprehensive energy optimization strategy that has both economic and environmental effects, contributing to compliance with international standards of sustainable development

Keywords: *energy efficiency, thermodynamic analysis, entropy, entropic analysis technologies, sustainability*

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DEVELOPMENT OF ENTROPY TECHNOLOGIES FOR ANALYSIS AND OPTIMIZATION OF ENERGY EFFICIENCY OF TECHNOLOGICAL SYSTEMS

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1. Introduction

In today's conditions of security and economic challenges, energy efficiency of enterprises is gaining strategic importance. Another important aspect is the greening of production by reducing energy consumption, which directly affects thermal pollution of the environment, greenhouse gas emissions and other harmful substances. Thus, by solving the energy problem, the enterprise not only reduces the cost of production, but also takes a step towards meeting international standards of sustainable development and "green" certifications.

The procedure for optimizing energy consumption is a complex task that encompasses a set of technical, technological and organizational measures. In general, it involves thermodynamic analysis, synthesis, selection of energy resources, selection or development of highly efficient equipment, optimization of technological processes, digital monitoring, analysis of energy consumption, etc.

However, the traditional understanding of the energy efficiency of the system does not provide a substantive answer to two fundamental questions: what is the cause of energy inefficiency and what energy efficiency potential the enterprise has. The complexity of this task is added by the fact that modern enterprises are hierarchical systems of inextricably linked elements of technological, heat-exchange, mechanical, and electrical equipment, where complex physical and chemical processes are simultaneously implemented, closely interacting. Therefore, to achieve the best results, it is necessary to approach the analysis systematically, taking into account the complexity of internal relationships, parameters, and characteristics.

A scientifically sound solution to the problem of energy efficiency is systemic thermodynamic and thermoeconomic optimization. The use of powerful tools of the second law of thermodynamics allows to find the right vector of an energy-efficient strategy in the simplest way, and the involvement of

economics allows to choose optimal solutions. Studies show that the economic and environmental effect of such solutions can be an order of magnitude higher than the improvement of individual technological processes.

The introduction of the concept of "exergy" into thermodynamics divided thermodynamic analysis into two approaches: entropic and exergy. As a result, "convenient exergy" has almost completely replaced the entropic concept to date. This has led to the fact that the focus of thermodynamic attention has shifted to "hypothetical workability", which, with the exception of heat engines, are not characteristic of technological systems. In many cases, the use of cyclical (exergy) technologies hides the natural cause of the system's imperfection, which can complicate optimization or make it of poor quality.

Therefore, the relevance of this scientific topic lies in substantiating the correct thermodynamic approaches and developing appropriate analysis and optimization technologies. In modern conditions, such thermodynamic models can be embedded in artificial intelligence algorithms (Digital Twins), which opens up new opportunities in the field of energy efficiency optimization.

2. Literature review and problem statement

In [1], the results of the study on various approaches to improving the energy efficiency of technological systems are presented. It is shown that the vast majority of modern study is focused on methodological and interdisciplinary approaches, the integration of renewable energy sources and the digitalization of energy systems.

In the context of the methodology of energy efficiency, three thermodynamic directions are distinguished: energy, exergy, entropy and their combinations with economic and environmental characteristics.

The variety of approaches allows to conclude that there is no single concept of optimizing energy efficiency. Obviously, the reason for this is the limited effectiveness of these tools in relation to complex systems of various purposes.

For example, in [2], an energy analysis of a cogeneration system combining an organic Rankine cycle and an ejector refrigeration unit was performed. The purpose of this analysis is to investigate the efficiency of using low-potential heat for the combined generation of electricity and cold. It is shown that the use of COP (Coefficient of Performance) and specific energy consumption allowed to make a basic assessment of the system. But the issues related to the objective reasons for inefficiency, thermodynamic perfection of the systems, economic and environmental characteristics remained unresolved. The reason for this result is only the quantitative assessment of energy transformations.

An option for overcoming the relevant difficulties is the use of exergy analysis, which allows simultaneously analyzing both quantitative and qualitative changes in the system. Over the past decades, the exergy method has become globalized and has gained practical application in various industries. In the publication [3], an exergy analysis of a thermal power plant was performed to study the impact of load on the efficiency of the system. As a result, the main sources of exergy losses were identified, and it was found that load optimization can significantly reduce irreversible losses. In the work [4], the energy and exergy efficiency of industrial boilers operating on coal were investigated. It is shown that exergy efficiency is significantly lower than energy efficiency, since it additionally

takes into account the internal irreversibility of processes. It is established that optimization of combustion processes and improvement of heat exchange surfaces have a positive effect on exergy indicators. In work [5], the exergy method was used to optimize low-temperature heat sources. The results of the study on a heat pump with a ground heat exchanger showed the largest exergy losses in the compressor and heat exchanger, which can be reduced by optimizing operating modes. Compared with energy analysis, exergy allowed achieving better thermodynamic results, which confirms the effectiveness and necessity of applying the second law of thermodynamics. This approach is fully justified for a heat engine in work [3]. But in [4, 5] there is no logical connection between the causes of inefficiency, losses of operability and real energy characteristics, especially in thermal interaction systems. Obviously, this is due to the inconsistency of the principles of exergy analysis with the technological purpose of the systems.

Also, previous studies have not resolved the issue of economic justification of thermodynamic recommendations. In many cases, the thermodynamic optimum does not coincide with the economic one. An option to solve this problem may be to supplement the thermodynamic analysis with an economic one. This is the approach used in [6], which considers a hybrid cogeneration and trigeneration system based on the organic Rankine cycle and a vapor-compressor refrigerator. Despite the high thermodynamic efficiency, the economic analysis showed that the system can be profitable only at high cost of electricity and availability of biomass. Thus, economic analysis can significantly affect energy-efficient solutions, but it is best applied in a hybrid version of exergoeconomic technologies.

This method was applied in the publication [7], which analyzed the system of combined generation of cold, heat and electricity using solar energy and biomass gasification. Exergoeconomic studies showed that the developed system has higher exergy efficiency than traditional ones, and the cost of energy resources depends on the share of solar energy and the cost of biomass. Another important issue that has not been addressed in previous works is the assessment of the impact of energy efficiency measures on the environmental characteristics of the enterprise. The authors of the work [8] solve this problem using 3E-analysis (Energy, Exergy, Environmental). A comprehensive study of the cogeneration system of an oil refinery allowed to determine the priorities for modernization taking into account environmental aspects. However, as in the case of economic-exergy analysis, a consistent exergy-environmental analysis, although it provides additional opportunities, significantly complicates the search for optimal solutions. An option for overcoming the complicated analysis can be a hybrid exergoecological method, which belongs to advanced exergy technologies. This is the approach used in [9], where the optimal configuration of a polygeneration system is determined. The analysis of the above studies confirms that hybrid exergy technologies are effective comprehensive tools for analyzing and optimizing systems based on heat engines. However, "exergy" gives rise to methodological contradictions in the case of analyzing heat technology systems, where the purpose of functioning is not to generate work as a useful product. The same problem arises in the case of heat engines, if they are part of a complex, ensuring the functioning of technological systems. In practice, this can lead to erroneous conclusions and complicate the search for optimal technical solutions.

An alternative may be the entropy approach, which, like the exergy approach, is based on the second law of thermodynamics, but is universal for systems of various purposes.

For example, in [10] the perfection of heat exchangers is determined based on the efficiency of entropy transfer and the local number of entropy generation. In [11], the efficiency of using nanofluids in thermosyphon heat pipes was investigated using entropy generation analysis. In [12], the efficiency of using artificial roughness of the absorber surface of a solar air heater was analyzed. The results of the studies presented show that in all three cases, the analysis methodology is focused on thermodynamic perfection and is based on the principle of minimizing entropy generation. This allows to identify the fundamental causes of system inefficiency and formulate a thermodynamic optimization strategy. However, this is not enough to solve the issue of energy efficiency, since there is no connection between the entropy generated by the system and the energy resources it consumes.

Thus, individual methods show good results in local areas, but there is no single system tool for analyzing the energy efficiency of complex complexes consisting of technological, heat exchange, mechanical and electrical systems.

All this allows to assert that it is advisable to conduct study devoted to the development of systems analysis technologies and optimization of energy efficiency of multi-purpose technological systems based on entropic characteristics.

3. The aim and objectives of the study

The aim of this study is to develop entropic technologies for system analysis and optimization of energy efficiency of technological systems and complexes for various purposes. This will make it possible to improve the energy, economic and environmental characteristics of technological systems of modern enterprises.

To achieve this aim, the following tasks are envisaged:

- to investigate the mechanisms of the influence of process irreversibility on the energy efficiency of systems;
- to perform an applied entropy-energy analysis of the system;
- to determine the specific energy resource consumption for compensating for process irreversibility;
- to establish the dependence between the generation of entropy from process irreversibility and the energy efficiency of the system.

4. Materials and methods

The object of the study is the energy efficiency of technological systems and complexes of modern enterprises.

The hypothesis of the study is that maximizing the energy efficiency of technological systems can be achieved by minimizing their thermodynamic imperfection. According to the second law of thermodynamics, this can be achieved by minimizing the generation of entropy from the irreversibility of energy technological processes implemented in the studied systems.

To simplify the analysis, some systems were considered as "closed" with the main flows of energy and entropy, and fuel

energy was considered to be entropic at the initial stage of energy transformations.

The study used theoretical and theoretical-applied methods, including: analysis, synthesis, idealization, methods of thermodynamic analysis and mathematical modeling of energy systems.

The main considerations and testing are shown on the example of the analysis of beet sugar production systems, which provides for both own generation of thermal and electrical energy, and multi-stage energy transformation in the relevant sections of technological processes.

In general, the energy transformations of a modern enterprise can be presented in the form of Fig. 1.

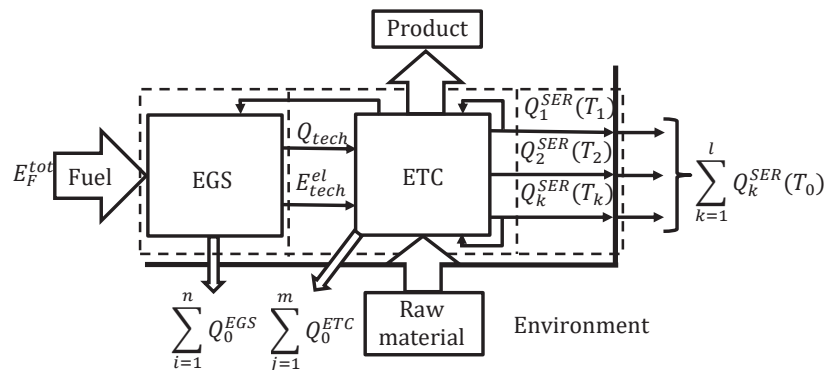


Fig. 1. Generalized view of energy transformations at the enterprise

Fuel energy in the form of heat Q_{tech} and electrical energy E_{tech}^{el} , resulting from the operation of the energy-generating system (EGS) ensures the implementation of technological processes in the energy-technological complex (ETC).

According to classical considerations, the energy efficiency of an enterprise is determined by the costs of fuel and energy resources or energy consumed for the production of a unit of output, which can be expressed through specific fuel consumption

$$f_{tech}^{tot} = \frac{\text{Fuel}}{\text{Product}}. \tag{1}$$

Obviously, increasing energy efficiency is possible by reducing fuel consumption while maintaining or increasing existing productivity.

Analysis of the general synthetic energy balances of the systems shown in Fig. 1 allows to establish the correspondence between fuel energy E_F^{tot} and other energy characteristics in three main variations:

$$E_F^{tot} = Q_{tech} + E_{tech}^{el} + \sum_{i=1}^n Q_0^{EGS}, \tag{2}$$

$$Q_{tech} + E_{tech}^{el} = \sum_{k=1}^l Q_k^{SER}(T_k) + \sum_{j=1}^m Q_0^{ETC}, \tag{3}$$

$$E_F^{tot} = \sum_{i=1}^n Q_0^{EGS} + \sum_{j=1}^m Q_0^{ETC} + \sum_{k=1}^l Q_k^{SER}(T_0), \tag{4}$$

where Q_{tech} , E_{tech}^{el} - respectively, the total thermal and ETC electrical load; $\sum_{i=1}^n Q_0^{EGS}$ - total heat losses in EGS; $\sum_{j=1}^m Q_0^{ETC}$ - total heat losses in ETC; $\sum_{k=1}^l Q_k^{SER}(T_k)$ - total heat of secondary energy resources (SER) leaving the ETC; $\sum_{k=1}^l Q_k^{SER}(T_0)$ - total heat losses of the SER.

According to equation (2), the energy demand provided by fuel combustion F_{tech}^{tot} in the EGS is mainly determined by the thermal and electrical loads of the ETC. This allows to divide the total fuel consumption F_{tech}^{tot} into thermal and electrical components and establish a connection with the corresponding energy characteristics:

$$F_{tech}^{tot} = F_{tech}^Q + F_{tech}^{el}; \tag{5}$$

$$F_{tech}^Q = \frac{Q_{tech}}{Q_c \eta_{EGS}^Q}; \tag{6}$$

$$F_{tech}^{el} = \frac{E_{tech}^{el}}{Q_c \eta_{EGS}^{el}}, \tag{7}$$

where η_{EGS}^Q and η_{EGS}^{el} – the EGS efficiency for the generated heat and electric energy, respectively; Q_c is the heat of combustion of the fuel.

Analysis of equations (5)–(7) shows that reducing the total fuel consumption implies reducing energy consumption for technological needs and increasing the generation efficiency. However, at this stage it is not yet clear how to achieve this.

A partial answer to this question is given by equation (3). It shows that the technological heat and electrical load mainly depend on the efficiency of the use of the SER, that is, on the total heat of unused low-potential flows $\sum_{k=1}^l Q_k^{SER}(T_k)$, leaving the ETC.

An important conclusion is also made by equation (4), which demonstrates that all the fuel energy through a sequence of energy transformations at the final stage is transferred to the environment (ENV) and is lost for technological use. The reason for this negative phenomenon is both the direct thermal interaction of high-potential heat flows with the ENV due to insufficiently effective insulation or technological process, and the discharge of heat from low-potential SERs into the ENV.

Summarizing the results of the analysis based on general production energy balances, it can be emphasized that such an approach allows to quickly establish quantitative relationships between the main energy characteristics of the enterprise and formulate the basic directions of the energy-efficient strategy at the first stage.

For example, the energy analysis of the ETC of a sugar factory according to the method of general production material and energy balances [13] allowed to obtain the main characteristics of the complex regardless of the analysis of internal heat-technological processes. The configuration of the heat-technological scheme of the enterprise and detailed characteristics are given in [14], and the main results are summarized in Tables 1, 2.

The total steam consumption for technological needs takes into account the amount of steam required for the implementation of heat-technological processes and the steam consumed to compensate for heat losses

$$\sum D_{tech} = D_{tech} + \sum D_0. \tag{8}$$

The unknown characteristics in Tables 1, 2 are determined from the general production synthetic material and energy balances:

– the equation of the general production synthetic material balance ETC

$$\begin{aligned} \sum D_{tech} + W_{bw}^{in} + G_{sh}(1 - DM_{sh}) = \\ = D_{s.va} + W_{con} + W_{ex} + W_{sat} + \\ + G_p(1 - DM_p) + G_m(1 - DM_m) + G_{fc}(1 - DM_{fc}); \end{aligned} \tag{9}$$

– the equation of the ETC general production synthetic energy balance

$$\begin{aligned} (H_s(\sum D_{tech}) + H_{sh} + H_{bw} + E_{el} = \\ = H_{con}(\sum D_{tech}) + H_{w.ex}(W_{ex}) + H_{s.va} + \\ + H_p + H_m + H_{fc} + H_{sug} + \sum Q_{0.ETC}. \end{aligned} \tag{10}$$

Table 1

Input component of the general production material and energy balance

No.	Product	Designation	Quantity, kg/t	Temperature, °C	Dry matter, DM %	Flow enthalpy, kJ/t
1	Shavings	G_{sh}	1000	10	25	36140
2	Barometric water	W_{bw}^{in}	877.4	10	–	36868
3	Total compensation of losses in ETC	$\sum D_0$	77	–	–	–
4	Technological steam	D_{tech}	D_{tech}	130	–	$H_s(D_{tech})$
5	Electric energy	E_{el}	–	–	–	108000

Table 2

Output component of the general production material and energy balance

No.	Product	Designation	Quantity, kg/t	Temperature, °C	Dry matter, DM %	Flow enthalpy, kJ/t
1	Condensate in CHP	W_{con}	W_{con}	105	–	$H_{con}(W_{con})$
2	Excess water	W_{ex}	W_{ex}	t_{ex}	–	$H_{ex}(W_{ex})$
3	Pulp	G_p	830	70	7.5	235861
4	Secondary steam of vacuum apparatus	$D_{s.va}$	81.67	72	–	214686
5	Molasses	G_m	34.34	70	82.5	5047
6	White sugar	G_{sug}	143.64	70	100	10510
7	Filter cake	G_{fc}	100	80	50	24000
8	Water losses at saturations	W_{sat}	11	–	–	28426
9	Total heat losses in ETC	$\sum Q_{0.ETC}$	–	–	–	232175

As a result, the following data were obtained:

- the total steam consumption for technological needs $\Sigma D_{tech} = 342.8 \text{ kg/t}$ or heat $Q_{tech} = 781.43 \text{ MJ/t}$;
- the amount of water discharged from the plant $W_{ex} = 711 \text{ kg/t}$.

According to equations (5)–(7), the corresponding fuel consumption was calculated:

- fuel consumption for the production of process steam in a CHP $F_{tech}^Q = 29.6 \text{ kg/t}$;
- fuel consumption for electricity production $F_{tech}^{el} = 4.49 \text{ kg/t}$;
- fuel consumption for technological needs and electricity production $F_{tech}^{tot} = 34.09 \text{ kg/t}$.

5. Results of the study of the energy efficiency of technological systems

5.1. Study of the irreversibility influence mechanisms of processes on the energy efficiency of technological systems

Using the main energy characteristics of ETC, a general energy analysis of EGS (for sugar production this is CHP) was performed in the form of a comparison of the main energy flows and the corresponding fuel equivalents (Fig. 2).

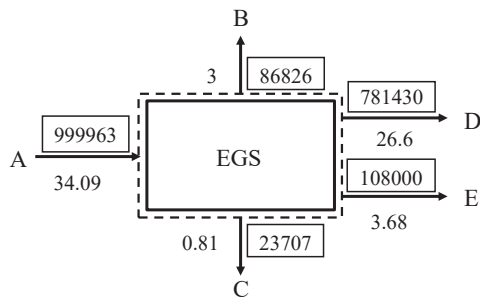


Fig. 2. Main energy flows (numerical values in the frame) and conventional fuel crossing the boundaries of the power generation system

In Fig. 2, flow A is the fuel energy, kJ/t, and the amount of conventional fuel, kg/t, entering the power generation system. Flows B and C are heat losses, kJ/t, and the equivalent amount of conventional fuel, kg/t, when generating heat and electricity, respectively. D and E are heat and electricity, kJ/t, and the equivalent amount of conventional fuel, kg/t, entering the power technology complex, respectively.

The results of the energy analysis show that only a small part of the total amount of fuel is spent on compensating for heat losses, in particular 3.81 kg/t, or 11%. At first glance, this system has no problems, and its energy efficiency can be improved by increasing the EGS efficiency on the generated heat η_{EGS}^Q and electrical energy η_{EGS}^{el} . However, during the generation of thermal and electrical energy, irreversible changes occur in the system: low-potential entropy-containing heat is generated, which has less technical value compared to the highly organized chemical energy of the fuel.

At the stage of EGS energy analysis, this problem almost does not manifest itself, but later negatively affects the ETC energy efficiency, leading to additional heat losses at the final stage of energy transformations. In order to fundamentally analyze this problem, energy transformations were studied from the point of view of the second law of thermodynamics.

To simplify and clarify the analysis, the thermal interaction of the system with the environment was considered using heat engines (Fig. 3) (subsystems "A" and "C"). In Fig. 3 shows two variants of such interaction: reversible (rev) using an ideal heat engine (heat engine HE) "A" and irreversible (irrev) using a real HE "C". It is important that the thermal interaction in both cases occurs within the same states, which corresponds to an absolutely identical change in thermodynamic parameters and state functions. It is this similarity that most often hides the irreversibility of processes during classical energy analysis, but the energy characteristics of these processes will differ.

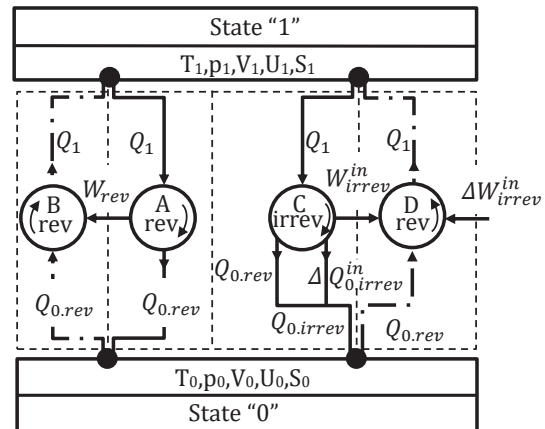


Fig. 3. Reversible and irreversible thermal interactions of the system with the environment using heat engines

Analysis of reversible energy transformations in subsystem "A" showed that the result of its functioning is the generation of a useful "energy product" in the form of maximum work W_{rev} and minimum heat $Q_{0,rev}$, which is transferred to the ENV. The reversibility of such an interaction is confirmed by the functioning of an ideal refrigeration machine RM (refrigeration machine). With the help of RM, using W_{rev} , the system can independently return to its initial state so that no changes will occur in the ENV as a result of both processes. Thus, the reverse process completely compensates for the direct one. In this sense, $Q_{0,rev}$ plays the role of functional costs.

If internally irreversible processes occur in the system, as, for example, in "C", then such a system is able to generate a smaller "energy product" W_{irrev}^{in} , but at the same time additionally gives heat to the ENV $\Delta Q_{0,irrev}^{in}$. Obviously, $\Delta Q_{0,irrev}^{in}$ is a consequence of the implementation of irreversible processes and under these conditions can justifiably be considered a loss of heat.

To return to the initial state using subsystem "D" (Fig. 3), in which, as in "B", internally reversible processes W_{irrev}^{in} occur, it is no longer enough. Therefore, compensation occurs at the expense of external energy in the amount

$$\Delta W_{irrev}^{in} = W_{rev} - W_{irrev}^{in}, \tag{11}$$

or

$$\Delta W_{irrev}^{in} = \Delta Q_{0,irrev}^{in} = Q_{0,irrev} - Q_{0,rev}. \tag{12}$$

Equations (11), (12) already at this stage allow to assess the impact of the irreversibility of processes on the energy characteristics of the system and draw important conclusions.

On the one hand, irreversibility leads to a decrease in the generation of a useful "energy product", and on the other hand, to additional heat losses in the ENV, which, according to equation (4), requires energy compensation. This conclusion is summarized in the "principle of energy compensation of irreversibility".

According to the second law of thermodynamics, using the entropy of irreversibility, it is possible to give quite specific values and link it with the energy characteristics of the system.

To do this, it is enough to compile and analyze the entropy balances for subsystems "A" and "C" (Fig. 3).

In subsystem "A" reversible processes occur, and therefore the change in entropy is determined only by thermal interaction with the ENV

$$(S_0 - S_1)_{rev} = -\frac{Q_{0,rev}}{T_0}. \quad (13)$$

In subsystem "C" in addition to thermal interaction, irreversibility leads to the generation of additional entropy S_{gen}^{in}

$$(S_0 - S_1)_{irrev} = -\frac{Q_{0,irrev}}{T_0} + S_{gen}^{in}. \quad (14)$$

Taking into account equations (12), (13) and (14), a connection is established between the energy characteristics of the system's functioning and the irreversibility of processes

$$\Delta W_{irrev}^{in} = \Delta Q_{0,irrev}^{in} = T_0 S_{gen}^{in}. \quad (15)$$

Equation (15) in classical thermodynamics is called the Guy-Stodola formula and is used to determine the loss of workability, and in thermodynamic analysis – to calculate the exergy losses of the system from the irreversibility of processes.

However, as shown above, in addition to the loss of workability, the product of the thermodynamic temperature of the ENV T_0 and the increase in the entropy of the system from the irreversibility of processes S_{gen}^{in} also shows additional heat losses caused by irreversibility.

This allows to draw the following conclusion: any generation of entropy from the irreversibility of processes leads to additional heat losses and, accordingly, requires energy compensation.

This approach can be a universal tool for analyzing energy technology systems of various types, since, regardless of the functional purpose, thermal interaction with the ENV, unlike mechanical, is inherent to all systems.

A similar result can be obtained in the case of external irreversibility of processes using the example of analyzing the thermal interaction of system "B" with the ENV (Fig. 4) due to the temperature difference $\Delta T = T_0' - T_0$.

Due to the irreversibility of thermal interaction, system "B" generates less work, and therefore the return to the initial state using system "C" requires additional energy compensation in the amount

$$\begin{aligned} \Delta W_{irrev}^{out} &= W_{rev} - W_{irrev}^{out} = \\ &= Q_1 \left(1 - \frac{T_0}{T_1}\right) - Q_1 \left(1 - \frac{T_0'}{T_1}\right) = Q_1 \frac{\Delta T}{T_1}. \end{aligned} \quad (16)$$

To confirm that, as in the case of internal irreversibility, the energy compensation of external irreversibility is proportional to the generation of entropy, it is necessary to prove the following equality

$$\Delta Q_{0,irrev}^{out} = \Delta W_{irrev}^{out} = T_0 S_{gen}^{out}. \quad (17)$$

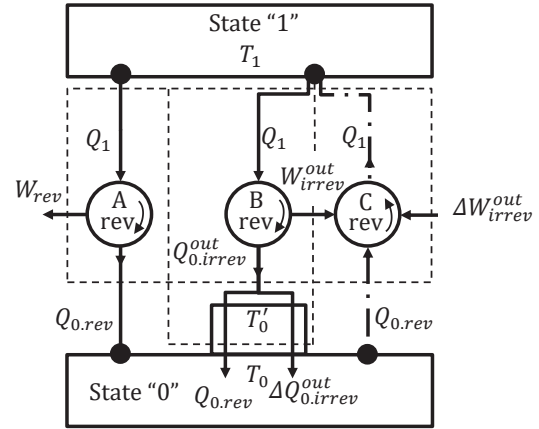


Fig. 4. Analysis scheme of external irreversible thermal interaction

Irreversible thermal interaction between two systems with different temperatures causes additional entropy generation in the amount

$$\begin{aligned} S_{gen}^{out} &= S_{gen}^T = \frac{Q_{0,irrev}^{out}}{T_0} - \frac{Q_{0,irrev}^{out}}{T_0'} = \\ &= Q_{0,irrev}^{out} \left(\frac{T_0' - T_0}{T_0' \cdot T_0} \right) = Q_{0,irrev}^{out} \frac{\Delta T}{T_0' \cdot T_0}. \end{aligned} \quad (18)$$

Substituting equation (18) into equation (17), after simplifications, a result was obtained that coincides with equation (16)

$$\begin{aligned} \Delta Q_{0,irrev}^{out} &= T_0 Q_{0,irrev}^{out} \frac{\Delta T}{T_0' \cdot T_0} = (Q_1 - W_{irrev}^{out}) \frac{\Delta T}{T_0'} = \\ &= Q_1 \frac{T_0'}{T_1} \frac{\Delta T}{T_0'} = Q_1 \frac{\Delta T}{T_1}, \end{aligned} \quad (19)$$

which in this case also confirms the principle of energy compensation of irreversibility.

5.2. Applied entropy-energy analysis of the energy-generating system of sugar production

Using the methodology of the presented analysis, a study of the thermodynamic efficiency of the EGS system of a sugar factory (CHP) was conducted in the context of "irreversibility-fuel". The initial data were taken from the previous example (Fig. 2). The thermodynamic temperature of the CHP T_0 was taken as the temperature of the chips and barometric water of 283.15 K. To simplify and make the calculations more informative, the CHP was considered as a closed thermodynamic system; only the energy transformations of fuel energy into the amount of heat and electric energy consumed by the ETC were taken into account.

The generation of entropy from the potential irreversibility of fuel energy in the amount $S_{gen}^{F,tot} = 3531.3 \text{ kJ}/(\text{t} \cdot \text{K})$ was calculated, considering it at the initial stage of energy transformations as an organized form of energy.

The increase in entropy from the useless thermal interaction of fuel energy with CHP during the generation of heat and electric energy for technological needs received the following values: $S_{gen,0}^Q = 306.6 \text{ kJ}/(\text{t} \cdot \text{K})$ and $S_{gen,0}^{el} = 83.7 \text{ kJ}/(\text{t} \cdot \text{K})$ respectively.

Considering the combined generation of heat and electricity, the total internal irreversibility of the EGS was

determined in two stages, assuming that the thermodynamic temperature of the working fluid in front of the turbine blades is $T_{tr}^{in} = 693.15$ K.

At the first stage, the increase in entropy from the conversion of chemical energy of the fuel into heat with temperature T_{tr}^{in} in the combustion and heat transfer processes was calculated by the equation

$$S_{gen.I}^{in} = \frac{Q_{tech} + E_{tech}^{el}}{T_{tr}^{in}} = 1283 \text{ kJ}/(\text{t} \cdot \text{K}). \quad (20)$$

At the second stage, the entropic equivalent of irreversibility during the generation of electricity was determined by comparing the real system with the reversible one. Thus, the reversible system can be represented as two consecutive reversible HE and HP (heat pump), the results of the energy analysis of which are presented in Fig. 5.

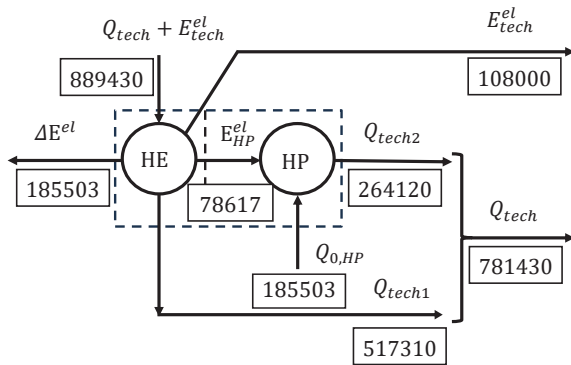


Fig. 5. Reversible combined heat and power generation system

Thus, the excess of electrical energy compared to the real CHP is

$$\Delta E^{el} = E_{max}^{el} - E_{tech}^{el} - E_{HP}^{el} = 185503 \text{ kJ}/\text{t}, \quad (21)$$

where E_{max}^{el} – the electrical energy generated by the reversible HE system.

Since this amount of ordered energy is unavailable in the case of the real system, this causes additional entropy generation

$$S_{gen.II}^{in} = \frac{\Delta E^{el}}{T_0} = 655 \text{ kJ}/(\text{t} \cdot \text{K}). \quad (22)$$

Therefore, the total entropy from all internally irreversible processes is

$$S_{gen}^{in,tot} = S_{gen.I}^{in} + S_{gen.II}^{in} = 1938 \text{ kJ}/(\text{t} \cdot \text{K}). \quad (23)$$

Taking into account the entropy that arises as a result of the thermal interaction of the EGS with the ENV, the total value of the entropy equivalent of the total irreversibility in the EGS was obtained

$$S_{gen.EGS}^{tot} = S_{gen}^{in,tot} + S_{gen.0}^Q + S_{gen.0}^{el} = 2328.3 \text{ kJ}/(\text{t} \cdot \text{K}). \quad (24)$$

The potential irreversibility in the ETC system was calculated, guided by the same principles:

$$S_{gen.ETC}^{el} = \frac{E_{tech}^{el}}{T_0} = 381.42 \text{ kJ}/(\text{t} \cdot \text{K}), \quad (25)$$

$$S_{gen.ETC}^Q = Q_{tech} \left(\frac{T_{ETC}^{in} - T_0}{T_{ETC}^{in} T_0} \right) = 821.58 \text{ kJ}/(\text{t} \cdot \text{K}), \quad (26)$$

$$S_{gen.ETC}^{tot} = S_{gen.ETC}^{el} + S_{gen.ETC}^Q = 1203 \text{ kJ}/(\text{t} \cdot \text{K}). \quad (27)$$

The generalized results of the entropy analysis are presented in Fig. 6.

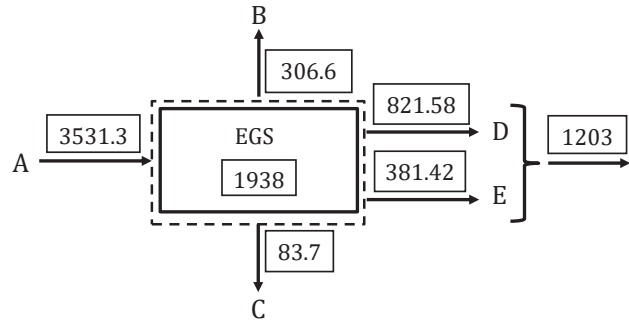


Fig. 6. Real and potential irreversibility of processes in the power generation system: flow A – fuel energy; flows B and C – heat losses; D and E – heat and electrical energy entering the energy technology complex

The validity of the previous considerations is easy to confirm if to write down the total entropy balance for the combined EGS+ETC system and compare this value with the potential entropy of fuel energy $S_{gen}^{F,tot}$, that will arise as a result of the completed sequence of irreversible processes

$$S_{gen}^{F,tot} = S_{gen.EGS}^{tot} + S_{gen.ETC}^{tot}. \quad (28)$$

5.3. Determination of the specific energy resource consumption for compensation of the irreversibility of processes

The obtained results allowed to combine the data of the energy and entropy analysis in the form of the specific consumption of conditional fuel for compensation of a unit of irreversibility

$$f_{irrev}^{comp} = \frac{F_{tech}^{tot}}{S_{gen.EGS}^{tot} + S_{gen.ETC}^{tot}} = 9.65 \frac{\text{g}}{(\text{kJ}/\text{K})}. \quad (29)$$

For an arbitrary EGS+ETC complex, a similar result can be obtained using the total energy and entropy balances.

According to Fig. 7

$$E_F^{tot} = \sum Q(T_0), \quad (30)$$

where $\sum Q(T_0) = \sum_{i=1}^n Q_0^{EGS} + \sum_{j=1}^m Q_0^{ETC} + \sum_{k=1}^l Q_k^{SER}(T_0)$ – the result of the thermal interaction of the components of the complex with the ENV.

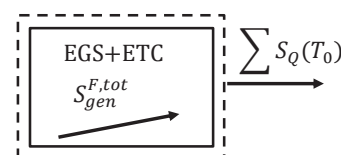


Fig. 7. Scheme of the general entropy balance of the enterprise

Then the total fuel consumption for the implementation of energy technological processes can be determined by the ratio

$$F_{tech}^{tot} = \frac{\sum Q(T_0)}{Q_c} \quad (31)$$

The general entropy balance of the EGS+ETC complex has the form (Fig. 7)

$$S_{gen}^{F,tot} = \sum S_Q(T_0) = \frac{\sum Q(T_0)}{T_0} \quad (32)$$

Taking into account equations (31) and (32), a universal equation is obtained for calculating the specific fuel consumption for compensation of irreversibility

$$f_{irrev}^{comp} = \frac{T_0}{Q_c} \quad (33)$$

Thus, the specific fuel consumption for compensation of irreversibility depends on the fuel type and the ENV temperature.

5. 4. Establishing the dependence between the generation of entropy from the irreversibility of processes and the energy efficiency of the system

Considering the previous results, the additivity of entropy and the principle of energy compensation of irreversibility, it is possible to determine the fuel consumption for compensation of irreversibility of any irreversible process

$$F_i^{comp} = f_{irrev}^{comp} S_{gen,i} \quad (34)$$

where $S_{gen,i}$ – the generation of entropy from the irreversibility of the i -th process.

And the total fuel consumption for technological needs is the sum of fuel consumption for compensation of irreversibility of processes implemented in the system

$$F_{tech}^{tot} = \sum F_i^{comp} = f_{irrev}^{comp} \sum S_{gen,i} \quad (35)$$

Using equation (34), fuel compensation equivalents were calculated for each irreversibility of the EGS system (Fig. 6); the obtained numerical values are plotted in Fig. 8 (numerical values without a frame).

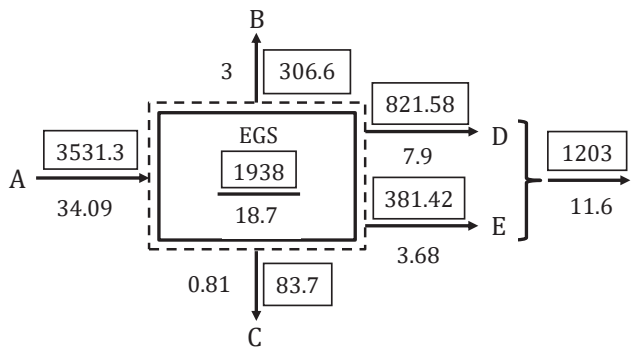


Fig. 8. Entropy generated from the irreversibility of processes (numerical values in the frame), and equivalents of conventional fuel used to compensate for the irreversibility; flow A – fuel energy; flows B and C – heat losses; D and E – heat and electrical energy entering the energy technology complex

The obtained data coincide with the results of the energy analysis, which confirms their reliability

$$F_{tech}^{tot} = F_{in.EGS}^{comp} + F_{Q.EGS}^{comp} + F_{el.EGS}^{comp} + F_{Q.ETC}^{comp} + F_{d.ETC}^{comp} = 34.09 \text{ kg/t.} \quad (36)$$

At the final stage, equation (1), taking into account equation (35), took on a new form

$$f_{tech}^{tot} = \frac{\text{Fuel}}{\text{Product}} = f_{irrev}^{comp} \frac{\sum S_{gen,i}}{\text{Product}} \quad (37)$$

As a result, the dependence of the energy efficiency of the EGS+ETS complex of the enterprise on the irreversibility of the processes implemented in it at all stages of energy technology transformations was obtained.

6. Discussion of the results of thermodynamic research of energy efficiency

Unlike energy analysis [13], the developed entropy-energy approach allows for a comprehensive assessment of energy transformations and identification of hidden sources of energy inefficiency. The new methodology, using the principle of energy compensation of irreversibility, already at the stage of entropy analysis makes it possible to determine fuel or energy equivalents necessary to compensate for the irreversibility of real processes. Thus, in comparison with exclusively entropy analysis [10–12], entropy-energy operates not with abstract characteristics of irreversibility, but with specific energy ones, which significantly simplifies and accelerates the optimization procedure.

For example, comparing the results of energy analysis in Fig. 2 and entropy-energy in Fig. 8, significant differences can be seen. The fuel equivalent of the flow D, which corresponds to technological heat in the amount of $Q_{tech} = 781.43 \text{ MJ/t}$, in Fig. 8 (7.9 kg/t) is significantly smaller than in Fig. 2 (26.6 kg/t). Obviously, such a large difference is explained by the low heat potential, which is taken into account by the entropy-energy analysis, unlike the energy analysis. In Fig. 8, there is a fuel equivalent of 18.7 kg/t, which compensates for the internal irreversibility of EGS processes, but which is not present in Fig. 2. This indicates that according to the results of the entropy-energy analysis, compensation for only the internal irreversibility of EGS processes consumes about 55% of the primary energy resource, while the energy analysis does not record this problem at all.

Therefore, a critical methodological problem arises when the energy-generating system can secretly consume about half of the potential of the primary energy resource. In practice, these costs imperceptibly fall on the balance of the energy-consuming system, within which they cannot be compensated by any energy-efficient measures. Therefore, when analyzing the causes of energy inefficiency, it is important to understand their nature, which energy analysis does not allow.

Unlike modern exergy technologies, entropy-energy analysis, which is at the initial stage of development, is limited to optimizing only the thermodynamic characteristics of systems operating in a stationary mode.

For comprehensive optimization, it is necessary to consistently apply thermodynamic, economic and environmental analysis. Such optimization is more complicated and, in some cases, less effective than hybrid exergy technologies, which is obviously a drawback that can be solved in the future by developing entropy-economic-ecological optimization technologies.

7. Conclusions

1. The study of the impact of process irreversibility on the energy efficiency of systems showed that any generation of entropy from process irreversibility leads to additional heat losses and, accordingly, requires energy compensation. This conclusion is summarized in the principle of energy compensation of irreversibility and is the basis of entropy-energy analysis. Considering that thermal interaction with ENV, unlike mechanical, is natural and inherent to all systems, such an approach can be a universal tool for analyzing and optimizing energy technology systems of various types.

2. Applied entropy-energy analysis of EGS confirmed the effectiveness of entropic technologies, revealing hidden causes of inefficiency. The results obtained show that due to the internal irreversibility of processes, the energy-generating system consumes 18.7 kg/t of conventional fuel, which is 55% of the total. In real systems, these costs fall on the ETC balance, where they can no longer be compensated by energy-efficient measures.

3. The proposed new characteristic – specific energy resource consumption for compensation of irreversibility – makes it possible to calculate the fuel compensation equivalent for any irreversible process. This creates conditions for a new type of analysis: cause (irreversibility) – consequence (fuel compensation). In particular, the fuel equivalent of heat entering the ETC for the implementation of energy technological processes, calculated using entropy technology, turned out to be only 7.9 kg/t, which is 18.7 kg/t less than the results of energy analysis. These data once again confirm that energy analysis does not identify internally irreversible processes at the stage of their occurrence, but transfers this irreversibility to the final stage of thermal interaction with the ENV.

4. The established dependence between the generation of entropy from the irreversibility of processes and the energy efficiency of the system has both methodological and applied significance. From a methodological point of view, the analysis of fuel or energy consumption for compensation of irreversibility allows a new approach to the idea of energy efficiency, bringing to the fore qualitative characteristics of processes. In fact, the energy efficiency strategy can be

reduced to a strategy for increasing the thermodynamic perfection of the system by minimizing entropy generation. In practical terms, the direct connection between the primary energy resource and the characteristics of processes allows for faster implementation of energy optimization of the project, since any measures to reduce entropy generation will lead to a proportional reduction in the consumption of the primary energy resource.

Conflict of interest

The authors declare that they have no conflict of interest regarding this study, including financial, personal, authorship or other nature, which could affect the study and its results presented in this article.

Financing

The study was conducted without financial support.

Data availability

The manuscript has no related data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

Authors' contributions

Sergii Samiilenko: Conceptualization, Methodology, Formal analysis, Writing – original draft; **Roman Hryshchenko:** Formal analysis, Writing – original draft; **Maksym Kryvosheiev:** Resources, Visualization.

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