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THERMODYNAMIC ANALYSIS OF SUGAR PRODUCTION HEAT TECHNOLOGICAL COMPLEX: ANALYSIS METHOD

Об'єктом дослідження є теплотехнологічні системи цукрового виробництва та теплотехнологічний комплекс в цілому. Сучасний цукровий завод є складною ієрархічною системою нерозривно пов'язаних між собою елементів, а його базис – теплотехнологічний комплекс – об'єднує елементи технологічного, теплообмінного, механічного обладнання, в якому одночасно реалізуються, тісно взаємодіючи, складні фізико-хімічні процеси. Враховуючи складність внутрішніх взаємозв'язків процесів, їх параметрів і характеристик, необхідно системно підходити до аналізу реального функціонування, оцінки ефективності та до розв'язання задач оптимізації комплексу в цілому, а також окремих його підсистем і елементів.

У роботі запропоновано методику термодинамічного аналізу теплотехнологічного комплексу цукрового виробництва як єдиної термодинамічної системи, що дозволяє аналізувати основні фактори впливу на енергетичну ефективність комплексу безвідносно до перебігу процесів, що реалізуються всередині системи. В основі методики спільний аналіз загальних синтетичних та аналітичних балансів маси, енергії та ентропії. Ця модель має глибоке фізичне підґрунтя, адже рівняння матеріального балансу є інтегральною формою запису закону збереження кількості речовини, рівняння енергетичного балансу – інтегральною формою запису першого закону термодинаміки, а рівняння ентропійного балансу – інтегральною формою запису другого закону термодинаміки. Основне завдання методики – швидка оцінка досконалості теплотехнологічного комплексу та його визначення «енергозберігаючого потенціалу». Також застосування принципу енергетичної компенсації необоротності та ентропійних критеріїв дозволяють визначити джерела та причини недосконалості систем, а складені рейтинги недосконалостей допомагають розробити систему заходів підвищення ефективності комплексу оптимальної послідовності. Тому запропонована методика термодинамічного аналізу, на відміну від методик, в основі яких ексергетичні характеристики, забезпечує комплексний аналіз, оперуючи лише фундаментальними законами та принципами класичної термодинаміки. А також може бути застосована як для оптимізації енергетичних характеристик діючих, так і під час проектування нових підприємств цукрової промисловості.

Ключові слова: *енергетична ефективність, необоротність процесів, термодинамічний аналіз, ентропійний метод, ресурсозбережні заходи.*

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1. Introduction

The main methodological problem in the implementation of resource-saving measures in the sugar industry is the lack of objective indicators for assessing energy efficiency. The procedure for analysis and optimization of the heat-technological complex (HTC) requires not only the determination of the totality of the absolute energy characteristics of the functioning of the complex, but also the establishment of criteria that would comprehensively and unambiguously characterize the energy transformations peculiar to sugar production systems. Obviously, such criteria should be scientifically based and meet the fundamental principles of the general methodology for optimizing heat transfer processes and systems, which is based on the indisputable fact of the existence of irreversibility as a physical source of inefficiency of technical systems. Therefore, it is urgent to develop a comprehensive methodology for thermodynamic analysis and optimization of the thermal characteristics of sugar production, including the assessment of the thermodynamic imperfection of the complex, the establishment of links between thermodynamic imperfection and energy efficiency, as well as the determination of the resource saving potential of typical enterprises.

2. The object of research and its technological audit

The object of research is the heat-technological systems of sugar production and the technological complex as a whole. *The subject of research* is the irreversible processes of energy conversion of various forms in the heat-technological complex of sugar production.

A modern sugar factory is a complex hierarchical system of inextricably interconnected elements, and its basis – HTC – combines the elements of technological, heat transfer, and mechanical equipment, in which complex physicochemical processes are simultaneously realized, closely interacting.

At a number of enterprises, the specific consumption of equivalent fuel for technological needs only approaches 3 % by weight of beets. Thus, enterprises have a strong potential for «energy saving», and therefore, the rational use of fuel and energy resources (FER) can provide a significant economic effect, primarily due to cheaper operating costs for fuel and electricity and, as a result, a reduction in the cost of sugar.

Successful implementation of such a task is possible provided that all types of energy are used efficiently at the appropriate stages of the process.

One of the most problematic places is the complexity of the internal relationships between systems, processes, their parameters and characteristics. This requires a systematic approach to the analysis of real functioning, evaluation of effectiveness and to solving the problems of optimization of the fuel and energy complex of the sugar plant as a whole, as well as its individual subsystems and elements.

3. The aim and objectives of research

The aim of research is development of a comprehensive methodology for thermodynamic analysis of HTC based on the general energy and entropy balances of the complex.

To achieve this aim, it is necessary to complete the following objectives:

1. Develop general production material, energy and entropy balances of HTC for sugar production.
2. Develop a methodology for constructing ratings of imperfection of HTC subsystems.
3. Establish a quantitative relationship between the irreversibility of processes and the energy efficiency of the HTC.

4. Research of existing solutions of the problem

Since the 70s of the XX century, numerous studies have been carried out aimed both at determining the general laws and properties of optimal chemical-technological systems, and at developing methods for their analysis and synthesis, including methods of thermodynamic analysis. Most of the modern works are represented by energy and exergy analysis of heat engines [1]. In particular, the authors of publications [2, 3] successfully investigated alternative technologies for improving the thermodynamic characteristics of energy-generating systems based on the organic Rankine cycle. Also of interest are works [4, 5] with thermodynamic modeling and economic analysis of cogeneration and trigeneration systems, including in sugar production. An alternative version of thermodynamic analysis is described in [6], however, this work shows the entropy analysis of only the heat exchanger. In recent years, borrowing the experience of thermodynamic analysis of heat engines, scientists are adapting the exergy method to the analysis of heat-technological systems of sugar production [7, 8]. The authors of [9] note that minimizing energy losses is a powerful tool for developing and managing the processes of efficient energy use. Also, an exergy analysis of the processes of production of raw sugar from sugar cane is presented in [10], but it is not clear whether the analysis results can be used for traditional technology. However, it is shown in [11] that despite the popularity of the exergy method, its application in sugar production is complicated by the thermodynamic incorrectness of the analysis of thermal processes using hypothetical loss of working capacity due to irreversibility.

Thus, the results of the analysis allow to conclude that it is necessary to use the second law of thermodynamics in the modern analysis of the energy efficiency of sugar production in sugar products, but it is advisable to implement this task on the basis of entropy analysis. According to the authors, the first stage of the study of the HTC energy efficiency should be a general analysis of the general synthetic and analytical balances of mass, energy and entropy, which will allow to evaluate the real perfection of the complex and determine the prospects for optimization.

5. Methods of research

It is assumed that the analysis is carried out in several stages, among which the main ones can be distinguished:

1. The parameters of all flows of substances and energy involved in energy transformations are determined.
2. The *energy* and *entropy* balances of subsystems, systems and the complex as a whole are composed, calculated and analyzed.
3. Based on certain energy and entropy characteristics, efficiency criteria are written based on the analysis of which conclusions are made about the effectiveness and causes of inefficiency from the process to the complex as a whole.

Despite the fact that the detailed HTC thermodynamic analysis is the most effective, its application is not always justified, since the implementation requires significant time and resource costs and a highly qualified engineer. This is especially true when it is necessary to quickly determine the energy efficiency of a real enterprise or to compare several alternative projects with each other.

6. Research results

This paper presents a methodology for the HTC thermodynamic analysis of sugar production, when the enterprise is considered as the only open thermodynamic system with the corresponding flows of matter and energy crossing its boundaries (Fig. 1). Such an idea, without going into details of the processes implemented within the system, makes it possible to connect the fuel and energy resources (FER) to the sources of their losses.

In this sense, *general production balances* (GPB) can become an important tool for analyzing the efficiency of using fuel and energy resources. In the future, GPB means the system of equations of the material, energy, and entropy balances recorded for the HTC as a whole. That is, if write down a closed system of analytical material, energy, and entropy balances for all interconnected elements of the HTC, then it will be simplified to a single GPB, the components of which will be flows that are not tied inside the system, but those that connect the HTC with the external environment (EE).

As will be shown below, such balances clearly make it possible to determine the main ways to reduce the consumption of fuel and energy resources and determine the effectiveness of their implementation.

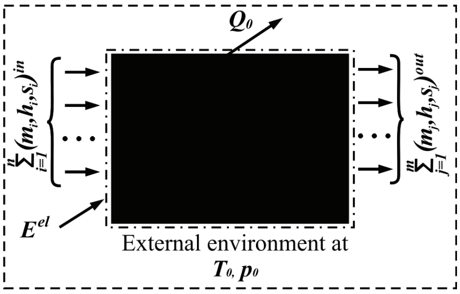

Fig. 1. Heat-technological complex as the whole thermodynamic system

Depending on the purpose of the compilation, GPB may be *actual or calculated*. So, when compiling the *actual* GPB according to the reporting data, all material, energy and entropy flows that enter the enterprise and leave it are determined.

And also the total value of non-current «loss» of energy is calculated, the absolute and relative indicators of thermodynamic efficiency.

To compile a *calculated* GPB, material flows and energy losses are determined, as in the preparation of analytical balances, or according to the results of the actual balance, or by methods that are irrelevant in the forefront. After that, energy and entropy flows are calculated, as a result of balancing of which they determine the energy consumption for production, absolute and relative indicators of thermodynamic efficiency.

When composing the HTC GPB, it is convenient to use this form of writing equations when all terms are absolute values. On the left side of the equation are written the terms that reflect the profitable component of the balance, on the right – the expense.

For HTC, the recording form of the expendable component necessitates the separation of GPB into synthetic and analytical. Let's explain this.

According to the definition, a synthetic balance establishes equality between intake and consumption (FER or energy).

This means that general production synthetic balances (GPSB) will have the following form (Fig. 2):

– general material balance:

$$\begin{aligned}&\sum D_s+W_{bw}+G_{sh}+G_l+G_{sg}+G_{air}^{in}=\\&=D_{mp}+W_{con}+W_{exc}+W_{sat}+G_{sug}+G_p+G_m+G_{fc}+G_{air}^{out},\end{aligned}\tag{1}$$

where $\sum D_s$ – steam for technological needs, kg/t; W_{bw} – barometric water, kg/t; G_{sh} – shavings, kg/t; G_l – lime, kg/t; G_{sg} – aturation gas, kg/t; G_{air}^{in} – air at the inlet to the HTC, kg/t; D_{mp} – massecuite pair, kg/t; W_{con} – condensate, kg/t; W_{exc} – excess water, kg/t; W_{sat} – water losses due to saturation, kg/t; G_{sug} – sugar, kg/t; G_p – pulp, kg/t; G_m – molasses, kg/t; G_{fc} – filter cake, kg/t; G_{air}^{out} – air at the HTC outlet, kg/t;

– total water balance:

$$\begin{aligned}&\sum D_s+W_{bw}+G_{sh}(1-CP_{sh})=D_{mp}+W_{con}+W_{exc}+W_{sat}+\\&+W_{air}+G_p(1-CP_p)+G_m(1-CP_m)+G_{fc}(1-CP_{fc}),\end{aligned}\tag{2}$$

where W_{air} – water, which is removed from the factory with air, kg/t; CP_i – dry substances of the i-th stream;

– energy GPSB:

$$\begin{aligned}&H_s+H_{bw}+H_{sh}+H_l+H_{sg}+H_{air}^{in}+E_{el}=H_{mp}+H_{con}+\\&+H_{exc}+H_{sat}+H_{sug}+H_p+H_m+H_{fc}+H_{air}^{out}+Q_0,\end{aligned}\tag{3}$$

where H_i – the flow enthalpy of the i-th stream at the corresponding temperature with which the stream enters or leaves the HTC; Q_0 – the general «loss» of heat to the environment from the surface of the heating equipment;

– entropy GPSB (let's compose in accordance with the properties of entropy, in which the latter can both rise and be diverted with flows of heat carriers and heat, and also grow from the irreversibility of processes):

$$\begin{aligned}&S_s+S_{bw}+S_{sh}+S_l+S_{sg}+S_{air}^{in}+\sum\Delta S_{irrev}^{s}=\\&=S_{mp}+S_{con}+S_{exc}+S_{sat}+S_{sug}+S_p+S_m+S_{fc}+S_{air}^{out}+S_0,\end{aligned}\tag{4}$$

where S_i – flow entropy of the i-th stream at the corresponding temperature with which the stream enters or leaves the HTC; $\sum\Delta S_{irrev}^{s}$ – increase in entropy from the irreversibility of processes in the HTC, calculated by the synthetic balance; $S_0=Q_0/T_0$ – change in the entropy of the environment.

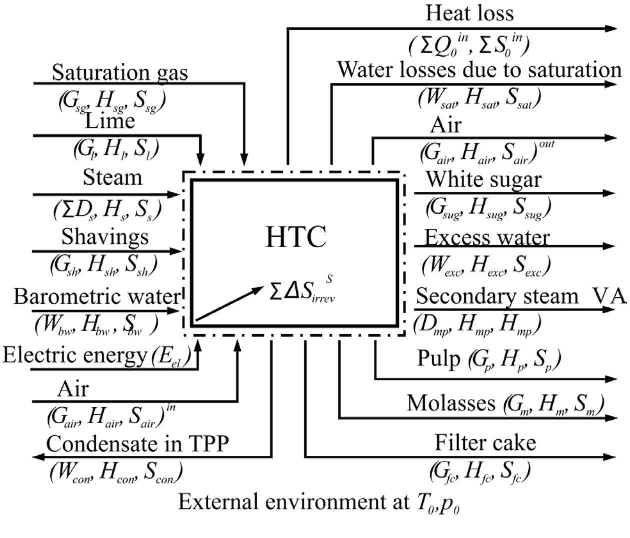

Fig. 2. Scheme of flows of matter, energy and entropy in the heat-technological complex (HTC) for the preparation of general production synthetic balances (GPSB): TPP – thermal power plant, VA – evaporator

The purpose of the analytical balance is to determine the depth and nature of the use of fuel and energy resources. Therefore, in the HTC case, general production analytic balances (GPAB) determine the distribution of summed fuel and energy resources for «useful use» in a given thermodynamic system and for «loss» in EE. Let's write the energy and entropy GPAB according to Fig. 3, the material balance will be identical to the balance (1).

Energy GPAB has the form:

$$\begin{aligned}&H_s+H_{bw}+H_{sh}+H_l+H_{sg}+H_{air}^{in}+E_{el}=\\&=H_{mp}(T_0)+H_{con}(T_{con})+H_{exc}(T_0)+H_{sat}(T_0)+H_{sug}(T_0)+\\&+H_p(T_0)+H_m(T_0)+H_{fc}(T_0)+H_{air}^{out}(T_0)+\sum Q_0.\end{aligned}\tag{5}$$

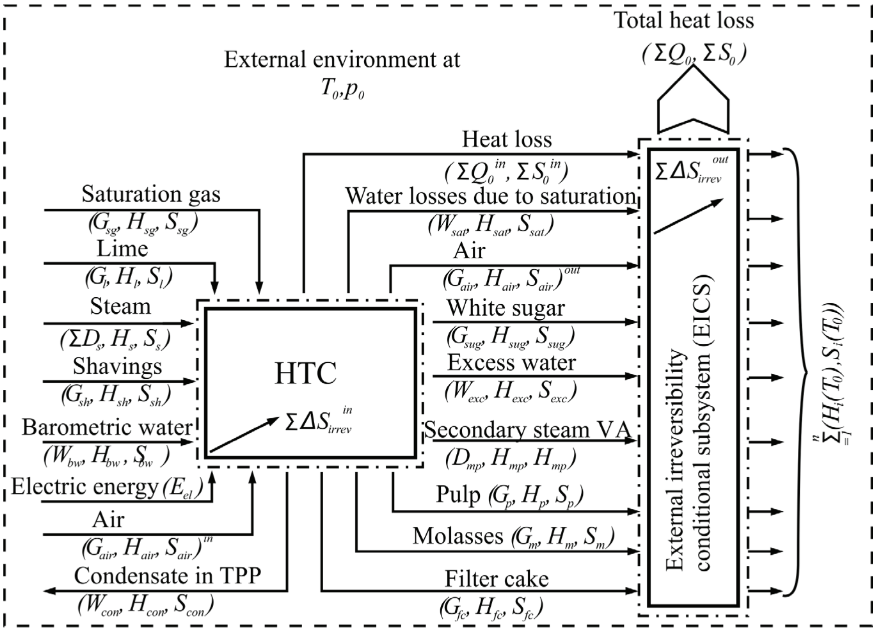

Fig. 3. Scheme of energy and entropy flows for the compilation of general production analytical balances of the heat-technological complex (HTC GPAB) of the sugar plant: TPP – thermal power plant, VA – evaporator

In equation (5), the total «losses» of heat, including the «losses» of heat from the surface of heat-technological complex (ΣQ_0^{in})) and from secondary energy resources (SER), which, based on the thermal current characteristics, have a temperature higher than the EE temperature (ΣQ^{SER}), are calculated as follows equation:

$$\Sigma Q_0=\Sigma Q_0^{in}+\Sigma Q_{SER}^{p}. \tag{6}$$

If the energy of the incoming flows of the SER subsystems of the external irreversibility conditional system (EICS) is designated as $\Sigma H_i(T_i)$, and the output is $\Sigma H_i(T_0)$, then the «loss» of heat from the SER is determined by the equation:

$$\Sigma Q_0^{SER}=\Sigma H_i(T_i)-\Sigma H_i(T_0). \tag{7}$$

Energy GPSB:

$$\begin{aligned}&S_s+S_{bw}+S_{sh}+S_l+S_{sg}+S_{air}^{in}+\Sigma\Delta S_{irrev}^{tot}=\\&=S_{mp}(T_0)+S_{con}(T_{con})+S_{exc}(T_0)+S_{sat}(T_0)+S_{sug}(T_0)+\\&+S_p(T_0)+S_m(T_0)+S_{fc}(T_0)+S_{air}^{out}(T_0)+\Sigma S_0,\end{aligned} \tag{8}$$

where $\Sigma S_0=\Sigma Q_0/T_0$ – entropy, which enters the EE with the total «loss» of heat; $\Sigma\Delta S_{irrev}^{tot}$ – overall increase in entropy during the HTC interaction in EE.

Substituting equation (6), (7) into (5) and shortening the like, let's obtain the energy GPSB equation (3). At first glance, the mathematical similarity of material and energy balances indicates the GPAB irrationality. However, a simple analysis of the entropy equations of GPSB (4) and GPAB (8) shows a difference in the numerical value of the increase in entropy.

So, $\Sigma\Delta S_{irrev}^{s}$ characterizes the internal irreversibility of the HTC processes and the irreversibility caused by heat transfer from the surface of the heat-processing equipment to EE ($\Sigma\Delta S_{irrev}^{0}$):

$$\Sigma\Delta S_{irrev}^{s}=\Sigma\Delta S_{irrev}^{in}+\Sigma\Delta S_{irrev}^{0}. \tag{9}$$

And $\Sigma\Delta S_{irrev}^{tot}$ is a numerical characteristic of the complete irreversibility of the combined HTC+EE system, which is expedient to divide into two components:

$$\Sigma\Delta S_{irrev}^{tot}=\Sigma\Delta S_{irrev}^{in}+\Sigma\Delta S_{irrev}^{out}, \tag{10}$$

where $\Sigma\Delta S_{irrev}^{in}$ – the increase in entropy from the irreversibility of the HTC – «internal irreversibility» internal processes; $\Sigma\Delta S_{irrev}^{out}$ – the increase in entropy from the irreversible interaction of the DER heat and the heat of «loss» from the surface of the heat-technological equipment from EE – *«external irreversibility»*.

To determine $\Sigma\Delta S_{irrev}^{in}$, let's write the balance of the entropy of the thermodynamic subsystem of the HTC (Fig. 3). In this case, let's assume that the heat ΣQ_0^{in} in leaves the system without changing the initial potential (the transformation takes place in the EICS):

$$\begin{aligned}&S_s+S_{bw}+S_{sh}+S_l+S_{sg}+\Sigma\Delta S_{irrev}^{in}=\\&=S_{mw}+S_{con}+S_{exc}+S_{sat}+S_{sug}+S_p+S_m+S_{fc}+\Sigma S_0^{in},\end{aligned} \tag{11}$$

where $\sum S_0^{in}=\sum_{i=1}^{n} Q_{0_i}^{in}/T_i$ – the entropy flow from the HTC subsystem to the EICS subsystem.

$\Sigma\Delta S_{irrev}^{out}$ is determined from the balance of the EICS subsystem (Fig. 3):

$$\begin{aligned}&S_s+S_{bw}+S_{sh}+S_{sug}+S_p+S_m+S_{fc}+\\&+\Sigma S_0^{in}+\Sigma\Delta S_{irrev}^{out}=S_{mw}(T_0)+S_{exc}(T_0)+S_{sat}(T_0)+\\&+S_{sug}(T_0)+S_p(T_0)+S_m(T_0)+S_{fc}(T_0)+\Sigma S_0.\end{aligned} \tag{12}$$

Therefore, it is possible to conclude that the entropy GPAB is of practical importance in the comprehensive entropy analysis of the HTC energy efficiency, since it allows to calculate the total irreversibility of the combined system of HTC+EE, which has an analytical relationship with fuel consumption and T_0.

Obviously, the introduction of the concepts of «*internal irreversibility*» and «*external irreversibility*» are effective in localizing sources of irreversibility – fuel consumers. To determine the influence degree of the components of equation (10) on the overall increase in entropy, the following coefficients can be used:

$$\omega^{in} = \sum \Delta S^{in}_{irrev} / \sum \Delta S^{tot}_{irrev}, \tag{13}$$

$$\omega^{out} = \sum \Delta S^{out}_{irrev} / \sum \Delta S^{tot}_{irrev}. \tag{14}$$

An important step in thermodynamic analysis is the construction of ratings of imperfections of the HTC – «*imperfection pyramids*» subsystems. Such hypothetical categories make it possible to evaluate the influence of individual components on the effectiveness of the overall system and to develop compensatory measures of optimal sequence. Given the entropy additivity, the technique is based on the use of relative irreversibility coefficients:

$$\omega_i = \frac{\Delta S_{irrev_i}}{\sum \Delta S_{irrev}}, \tag{15}$$

where ΔS_{irrev_i} – growth of entropy from the irreversibility of processes in the i-subsystem; $\sum \Delta S_{irrev}$ – growth of entropy from the irreversibility of processes in the general system, the component of which is the object of analysis.

For maximum localization of irreversibility, let's distinguish three groups of ratings:

1) «internal imperfection pyramid»:

$$\omega_i^{in} = \frac{\Delta S^{in}_{irrev_i}}{\sum \Delta S^{in}_{irrev}}, \tag{16}$$

where $\Delta S^{in}_{irrev_i}$ – growth of entropy from the irreversibility of processes in the i-th HTC subsystem;

2) «external imperfection pyramid»:

$$\omega_i^{out} = \frac{\Delta S^{out}_{irrev_i}}{\sum \Delta S^{out}_{irrev}}, \tag{17}$$

where $\Delta S^{out}_{irrev_i}$ – growth of entropy from the irreversible interaction of the i-th SER with EE (from the irreversibility of processes in the external conditional system of the EICS control unit);

3) «general imperfection pyramid»:

$$\omega_i^{tot} = \frac{\Delta S_{irrev_i}}{\sum \Delta S^{tot}_{irrev}}. \tag{18}$$

To determine the thermodynamic imperfection of HTC subsystems and systems, let's suggest to use the *entropy imperfection coefficient* [1]:

$$\eta_s^{imp} = \frac{\Delta S^{tot}_{irrev}}{\Delta S^{\max}_{irrev}}, \tag{19}$$

where ΔS^{tot}_{irrev} – total growth of entropy in the system as a result of the irreversibility of the processes implemented in it, W/K; $\Delta S^{\max}_{irrev}$ – maximum possible increase in entropy in the system, W/K.

The denominator of coefficient (19) plays the role of potential and is determined from the consequences of the second law of thermodynamics: in irreversible processes, the transition of the system to an equilibrium state occurs with an increase in entropy to a certain maximum value.

For example, for the energy of the flow of matter entering the subsystem ***A*** (Fig. 4 and is involved in energy transformations, the maximum potential response is possible with irreversible heat transfer by EE (subsystem ***C***)). In this case, the pressure wear is achieved due to dissipative phenomena, after which the dissipation energy in the form of heat passes to the EE temperature level. This means that, as a result of the interaction of the imaginary system in terms of EE, it quantitatively characterizes the possible maximum irreversibility of processes in the system during the transition from state 1 to state 2. Obviously, this thermodynamic quantity can be called the potential irreversibility of processes, the analytical expression for which in the case of stationary flow is recorded from the entropy balance of the combined *AC* thermodynamic system (Fig. 4):

$$\Delta S^{\max}_{irrev} = (S_2 - S_1) + \frac{|Q|_1^2}{T_0} + \frac{|E^D|_1^2}{T_0}, \tag{20}$$

where $|Q|_1^2 = U_1 - U_2$ – heat flux to EE when the temperature of the flow changes from T_1 to T_2; $|E^D|_1^2 = V(p_1 - p_2)$ – heat flow to EE during the dissipation of the mechanical energy of the flow (pressure change from p_1 to p_2).

Obviously, equation (20) can be rewritten in a more traditional form:

$$\Delta S^{\max}_{irrev} = (S_2 - S_1) + \frac{H_1 - H_2}{T_0}. \tag{21}$$

EE use as a separate, independent thermodynamic system is an integral component of the analysis based on the second law of thermodynamics. In this sense, the EE thermodynamic temperature T_0 is assigned the role of the base coordinate in determining the technical value of the energy of various potentials.

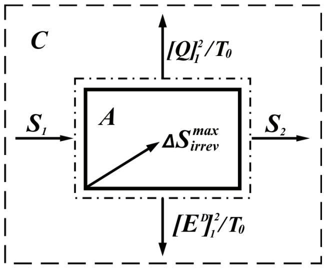

Fig. 4. Hypothetical system

To determine T_0, let's consider the reverse interaction of the HTC with EE. Obviously, such a limiting case assumes maximum energy efficiency, which, in turn, is impossible without the full use of the SER heat. Thus, an ideal system will include only cold flows – energy consumers, which in the general case are represented by chips, barometric water and atmospheric air.

Since the reverse thermal interaction in a non-cyclic form is possible only in the isothermal process, and the general change in the entropy of the combined adiabatic system HTC+EE is written as follows:

$$S_0^{HTC} + S_0 = 0, \tag{22}$$

or

$$\frac{Q_0}{T_0} - \frac{Q_0}{T_{ev}^{HTC}} = 0, \tag{23}$$

then $T_0 = T_{ev}^{HTC}$.

In equation (23) T_{ev}^{TTK} – weighted average thermodynamic temperature of cold flows, K. That is, in the general case, T_0 can be determined from the heat balance equation:

$$H_{bw}(T_{bw}) + H_{sh}(T_{sh}) + H_{air}^{in}(T_{air}) =$$
$$= H_{bw}(T_0) + H_{sh}(T_0) + H_{air}^{out}(T_0). \tag{24}$$

The right side of equation (24) is written in abbreviated form in order to simplify the calculations.

A similar result can be obtained by compiling the entropy GPAB of the previous conditions. For full compliance, let's write the equation in expanded form:

$$S_{bw}(T_{bw}) + S_{sh}(T_{sh}) + S_{air}^{in}(T_{air}) =$$
$$= S_{mw}(T_0) + S_{exc}(T_0) + S_{sat}(T_0) + S_{sug}(T_0) + S_p(T_0) +$$
$$+ S_m(T_0) + S_{fc}^{w}(T_0) + S_{air}^{out}(T_0), \tag{25}$$

where $S_{fc}^{w}(T_0)$ – the entropy of the water contained in the filter cake at EE temperature.

Above, the absolute characteristics of the irreversibility of various contents are determined that make it possible to establish an analytical relationship between the increase in entropy, the temperature of the nanowires, and the consumption of energy or fuel for the technological process. Despite the thermodynamic specifics of such a relationship (the second law of thermodynamics works), it is advisable to formulate the thesis of the previous sentence more correctly: *energy is spent on compensating the irreversibility of the HTC processes*. This approach opens up new possibilities in systemic thermodynamic analysis. Let's consider in more detail.

In general terms, the energy transformations of a sugar enterprise can be represented in such a way that the TPP is the source of the corresponding forms of energy, and the HTC and EE are a giant heat exchanger of maximum irreversibility (Fig. 5).

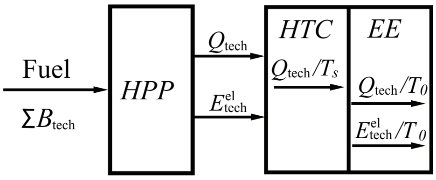

Fig. 5. General energy and entropy transformations of a sugar enterprise

According to classical considerations, the bulk of the fuel supplied to the HPP (ΣB_{tech}) is spent on the generation of heat (Q_{tech}) and electric energy (E_{tech}^{el}), which are necessary for the implementation of the process. Let's divide ΣB_{tech} into two components and establish a connection with the corresponding energy characteristics according to well-known equations:

$$\sum B_{tech} = B_{tech}^{Q} + B_{tech}^{el}; \tag{26}$$

$$B_{tech}^{Q} = \frac{Q_{tech}}{Q_n^p \eta_{HPP}^{Q}}; \tag{27}$$

$$B_{tech}^{el} = \frac{{}^{el}_{tech}}{Q_n^p \eta_{HPP}^{el}}, \tag{28}$$

where η_{HPP}^{Q} and η_{HPP}^{el} – HPP efficiency for the generated heat and electric energy, respectively.

Let's analyze the energy transformations from the point of view of the second law of thermodynamics. So, the chemical (free) energy of the fuel is removed from the state of thermodynamic equilibrium in the thermal power plant on the way to equilibrium by EE through the HTC thermodynamic system (Fig. 5), in which the useful potentials are fully triggered through a sequence of irreversible processes. Since the potentials are worn out, such energy loses its meaning, and therefore it resumes high potential due to fuel. It is important that the method of energy balances does not record any changes – the amount of energy at the entrance to the HTC and at the output is the same. As it is known, in practice this paradox is corrected by the introduction of two anthropomorphic concepts: «*efficiently-used energy*» and «*loss*», none of which corresponds to the content of the law of conservation of energy. Thus, in the energy approach, let's analyze the consequences, ignoring the reasons. But, if the principle of «*energy compensation of irreversibility*» is taken as the basis of the analysis of efficiency, then let's get a direct relationship: *fuel (energy) – irreversibility – efficiency.*

The total increase in entropy, which is determined from the GPAS equation (8), is written as the sum of two terms:

$$\sum \Delta S_{irrev}^{tot} = \sum \Delta S_{irrev}^{Q} + \sum \Delta S_{irrev}^{el}. \tag{29}$$

The first term characterizes the irreversible interaction of heat with EE:

$$\sum \Delta S_{irrev}^{Q} = Q_{tech}\left(\frac{T_s - T_0}{T_s T_0}\right), \tag{30}$$

where T_s – temperature of steam saturation at the inlet to the HTC.

The second is the dissipation of electrical energy with subsequent heat transfer also in the EE:

$$\sum \Delta S_{irrev}^{el} = \frac{E_{tech}^{el}}{T_0}. \tag{31}$$

Next, let's substitute equation (30) and (31) into (27) and (28), respectively. Let's assign new variables to the formed permanent complexes:

- specific fuel consumption for irreversibility compensation from thermal interaction:

$$b_T = \frac{T_s T_0}{(T_s - T_0) Q_n^p \eta_{TPP}^{Q}}; \tag{32}$$

- specific fuel consumption for irreversibility compensation from the dissipation of electrical energy:

$$b_D = \frac{T_0}{Q_n^p \eta_{HPP}^{el}}. \tag{33}$$

As a result, let's obtain the ratio for calculating fuel consumption to compensate for the general irreversibility of thermotechnological processes based on energy (the so-called «physical») and entropy approaches:

$$B^{Q}_{tech} = \sum \Delta S^{Q}_{irrev} b_T \ ; \tag{34}$$

$$B^{el}_{tech} = \sum \Delta S^{el}_{irrev} b_D . \tag{35}$$

Considering the content of the previous equations and the additivity of entropy, let's conclude*: any thermodynamic system in which irreversible processes of various nature are realized is a consumer of fuel whose energy is spent on compensation of irreversible changes. Thus, fuel consumption can be represented as a product of the increase in entropy from the irreversibility of processes by the corresponding proportionality coefficient:*

$$B_i = \Delta S^{Q}_{irrev\,i} b_T + \Delta S^{el}_{irrev\,i} b_D \ , \tag{36}$$

where B_i – fuel consumption to compensate for the irreversibility of processes in the *i*-th HTC subsystem; $\Delta S^{Q}_{irrev\,i}$ – increase in entropy from the irreversibility of heat transfer; $\Delta S^{el}_{irrev\,i}$ – growth of entropy from the dissipation of an ordered form of energy.

Therefore, the total fuel consumption can be rewritten as follows:

$$\sum B_{tech} = \sum_{i=1}^{n} B_i , \tag{37}$$

where n – the number of HTC subsystems.

In a similar way, it is possible to establish a relationship between fuel consumption and internal and external irreversibility of the HTC. For this, it is necessary to divide the growth of entropy by the sources of generation:

$$\sum \Delta S^{in}_{irrev} = \sum_{in} \Delta S^{Q}_{irrev} + \sum_{in} \Delta S^{el}_{irrev} , \tag{38}$$

$$\sum \Delta S^{out}_{irrev} = \sum_{out} \Delta S^{Q}_{irrev} + \sum_{out} \Delta S^{el}_{irrev} . \tag{39}$$

Then the fuel consumption equation for the compensation of internal and external irreversibility of the HTC will take the form:

$$B^{in}_{tech} = \sum_{in} \Delta S^{Q}_{irrev} b_T + \sum_{in} \Delta S^{el}_{irrev} b_D , \tag{40}$$

$$B^{out}_{tech} = \sum_{out} \Delta S^{Q}_{irrev} b_T + \sum_{out} \Delta S^{el}_{irrev} b_D . \tag{41}$$

Testing of the research results took place both at international conferences and in industrial conditions at Ukrainian enterprises of sugar production.

7. SWOT analysis of research results

Strengths. The developed methodology for thermodynamic analysis of the sugar and fatty complex of sugar production allows to analyze the main factors of influence on the energy efficiency of the complex regardless of the course of the processes implemented within the system. Using the principle of energy compensation of irreversibility and entropy criteria allows to determine the sources and causes of system imperfections, and imperfection ratings are compiled to help develop a system of measures to improve the HTC efficiency of optimal sequence.

Weaknesses. At this stage of the study, there is no single criterion of efficiency that would comprehensively characterize the energy efficiency of sugar production complex in sugar production, under certain conditions it may complicate the procedure of comparative analysis of the level of perfection of existing and proposed thermal schemes.

Opportunities. The proposed methodology of thermodynamic analysis allows the following:

- develop a system of measures to increase energy efficiency at the appropriate stages of the reconstruction of sugar enterprises;
- when realizing processes is idealized, determining their minimum possible irreversibility and the minimum possible fuel consumption for the sugar beet production process will be the basis for developing a comprehensive criterion for the energy efficiency of HTC sugar production.

Threats. Achieving the best energy efficiency indicators at the sugar industry is possible provided that this issue is comprehensively addressed. For this, a consistent legislative and economic policy of the state in the field of «energy conservation» and environmental protection has become no less important than the scientific and methodological foundations of energy analysis and optimization.

8. Conclusions

1. The general production material, energy, and entropy balances of HTC of sugar production have been developed, which are the basis of the methodology of thermodynamic analysis of the complex as a single thermodynamic system. This approach allows to quickly analyze the main factors affecting the energy efficiency of the complex, regardless of the course of the processes implemented within the system.

2. A methodology has been developed for constructing ratings of imperfection of HTC subsystems based on entropy characteristics. To maximize the localization of irreversibility, three groups of ratings were proposed: the «internal imperfection pyramid», the «external imperfection pyramid» and the «general imperfection pyramid».

3. A quantitative relationship has been established between the irreversibility of processes and the HTC energy efficiency through the assertion that *any thermodynamic system in which irreversible processes of various nature are realized is a consumer of fuel which energy is spent on compensation for irreversible changes*. Thus, fuel consumption can be represented as a product of the increase in entropy from the irreversibility of processes by the corresponding proportionality coefficient $B_i = \Delta S^{Q}_{irrev\,i} b_T + \Delta S^{el}_{irrev\,i} b_D$.

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