

*A procedure for analyzing the effectiveness of using fuel and energy resources (FER) in sugar production, based on the developed idealized circuit of the thermal-technological complex (TTC) as the base for comparison was presented. This procedure makes it possible to quantify the level of perfection of existing and proposed thermal circuits, as well as the impact of measures for enhancing energy efficiency on their perfection.*

*By idealizing technological and energy processes, a hypothetical TTC was synthesized, for which the minimum possible energy and entropy characteristics are determined. Under these conditions, the minimum possible heat consumption for the implementation of technological processes according to the classical heat technology circuit was calculated – 118.40 MJ/t; a “minimum” total increase in entropy from irreversible processes of the HTC – 314.68 kJ/(t·K); a minimum complex magnitude of specific consumption of conventional fuel – 0.8 % to m. b.*

*The determined characteristics are absolute criteria for the efficiency of sugar production systems, since it is impossible to reach lower values under existing technology, quality of raw materials and other conditions. The content of the criteria of energy efficiency of TTC was stated and the system of coefficients was proposed: coefficient of total energy efficiency of the TTC, coefficient of energy efficiency of the system of heat supply of the technological processes and coefficients of energy efficiency of internal and external structures of the TTC. The proposed criteria provide an objective and thermodynamically correct characteristic of the TTC of different structures.*

*The presented results of analysis of various measures for increasing the energy efficiency of sugar production show that only a gradual comprehensive reconstruction of an enterprise makes it possible to consistently reduce the FER consumption for technological needs, approaching the boundary values*

*Keywords: sugar production, thermodynamic analysis, entropy method, energy efficiency, resource-saving measures*

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# THERMODYNAMIC ANALYSIS OF THE THERMAL-TECHNOLOGICAL COMPLEX OF SUGAR PRODUCTION: CRITERIA FOR ENERGY EFFICIENCY OF AN ENTERPRISE

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## 1. Introduction

Global trends of introduction of energy-efficient technologies and making production environmentally friendly are also relevant for sugar enterprises, which in most cases require comprehensive modernization.

A modern sugar enterprise is a complex system of inextricably linked elements of technological, heat exchange and mechanical equipment, where complex physical and

chemical processes are simultaneously implemented, closely interacting. That is why when analyzing the effectiveness of using FER, the main methodical problem is to select objective criteria for quantitative assessment. It is important that such criteria should be scientifically substantiated and meet fundamental principles of the general methodology for optimizing heat exchange processes and systems.

The procedure of comparing the indicators of FER consumption of the proposed TTC with the indicators of the

existing circuit, which is subjective, since it does not characterize the level of energy perfection of a thermal circuit, dominates in sugar production.

Thus, the relevant problem is to develop comprehensive efficiency criteria, the use of which will make it possible to effectively develop and implement modern systemic measures to increase energy efficiency of sugar enterprises.

## 2. Literature review and problem statement

In modern studies of the properties of optimal chemical and technological systems, as well as of methods of their analysis and synthesis, it is noted that the promising direction is the development of methods for thermodynamic and thermo-economic analysis. In particular, in paper [1], the author explains this by the fact that an enterprise from the energy point of view is a thermodynamic system in which irreversible processes of different nature are implemented. A significant advantage of the thermodynamic approach is the absence of the need to analyze internal processes at the micro level, which makes it possible to quickly link the parameters of the system to its optimal energy characteristics. In publication [2], the author emphasizes the need to apply jointly the first and second laws of thermodynamics.

Although most modern works are represented by energy and exergy analysis of thermal machines, in recent years, borrowing this experience, scientists are adapting the exergy method to analysis of thermal manufacturing systems of sugar production. Thus, in paper [3], the authors consider the exergy analysis of a sugar enterprise, studying the ways to save energy resources with the help of thermodynamic tools. The continuation of the study was published in article [4], where it is emphasized that the optimization of thermodynamic characteristics of an enterprise allowed increasing its exergy efficiency up to 37.4 %. The obtained result is higher than in similar study [5].

However, it was shown in article [6] that the exergy approach somewhat complicates the analysis procedure due to thermodynamically incorrect assessment of the efficiency of thermal processes through hypothetical losses of workability, and exergy efficiency is ineffective to analyze an enterprise in general. That is why the authors preferred entropy characteristics that do not

have this disadvantage. But this solved the problem only partially, since the problem of the criterion that would comprehensively characterize energy efficiency of sugar production remains open. After all, traditional comparison of specific fuel consumption in order to analyze the level of perfection of existing and proposed thermal circuits is subjective and, in most cases, little informative, which is clearly seen from the following example.

According to [7], specific complex fuel consumption for sugar production is equal to the sum of specific fuel consumptions to generate thermal and electric energy, as well as fuel consumption to produce lime and saturation gas. Table 1 shows summarized data of energy consumption at various enterprises of sugar industry. The mean magnitudes of specific energy consumption, which are typical of most enterprises of Ukraine, are accepted as the basic indicators. In particular, in paper [8], taking into consideration the actual working conditions when pumping diffusion juice of 120 % to m.b. and thickening the syrup up to 72 % of DM, the prospective magnitude of fuel consumption for the production of thermal energy in the amount of 3.4 % to m.b. was determined. Comparing this value with the data from Table 1, it is evident that it is inferior to modern actual results.

That is why the problem to what magnitude it is theoretically possible to reduce specific magnitudes of FER consumption for manufacturing needs of beet sugar production remains open.

Table 1

Generalized data on energy consumption by sugar industry enterprises

Value	Specific fuel consumption for beetroot processing, Mkkal (MJ)/t. b.	Specific fuel consumption at TEC for heat production, kg c.f./Mcal(Mj)	Specific consumption of electric energy for beetroot processing, kW·h./t. b.	Specific fuel consumption at TEC for production of electric energy, kg g.f./kW·h	Specific consumption of lime for cleaning, % CaO to m.b.	Specific fuel consumption for lime production, kg c.f./t CaO
Basic indicators	230 (960)	0.175 (0.042)	27.0	0.178	1.8	0.17
Best indicators of plants in Ukraine	140 (590)	0.160 (0.038)	22.0	0.166	1.2	0.142
Best world indicators (potentially possible level)	92 (385)	0.154 (0.037)	15.0	0.151	1	0.135
Specific fuel consumption for basic level, % to m.b.	4.03		0.48		0.31	
Specific fuel consumption for best national level, % to m.b.	2.24		0.37		0.17	
Specific fuel consumption for best world level, % to m.b.	1.42		0.23		0.14	
Comprehensive specific fuel consumption for basic level, % to m.b.			4.8			
Comprehensive specific fuel consumption for best national level, % to m.b.			2.8			
Comprehensive specific fuel consumption for best world level, % to m.b.			1.8			

In thermodynamics, some relevant idealized objects, in which reversible processes are traditionally used as a comparison base for objective analysis of efficiency of thermodynamic processes and systems. These include the well-known “Carnot cycle”, “Rankine cycle”, “adiabatic turbine”, etc. The effectiveness of actual objects is determined by comparing their indicators with indicators of changes in mode parameters that are ideal in the appropriate range.

That is why it seems logical to develop such idealized circuits of the TTC of a sugar plant, the performance of which would minimally depend on the equipment design and would be determined, first of all, by possible boundary values of mode parameters.

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### 3. The aim and objectives of the study

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The purpose of the research is to develop a system of scientifically grounded criteria for energy efficiency of the TTC of sugar production. This will make it possible to quantify the level of perfection of thermal circuits, as well as to analyze various measures to increase energy efficiency of sugar enterprises.

To accomplish the aim, the following tasks have been set:

- to formulate the principles and limits of idealization of actual technological and energy processes of the TTC in order to determine the maximum possible potential for the implementation of resource-saving measures;
- to perform comprehensive analysis of the idealized TTC of sugar production;
- to formulate criteria for energy efficiency for the TTC as a whole;
- to test the developed criteria on the example of analysis of the phased implementation of measures to increase energy efficiency of a sugar enterprise.

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### 4. Materials and methods of research

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The existing technology of sugar production involves multi-stage heating of products and evaporation of a fairly significant amount of water from sugar solutions, which is why the minimum possible irreversibility is determined mainly by the technological processes used to obtain sugar. It can be determined based of the degree of their idealization, that is, on condition of maximum possible alignment of temperatures and concentrations, minimal dissipation of mechanical energy, as well as the assumption of the absence of energy “losses” to the environment.

To determine the minimum possible energy and entropy characteristics of the idealized TTC, we used the methods for energy and entropy analysis, as well as the preliminarily developed method for analysis of general production balances [6]. This approach allowed limiting to analysis of total flows of mass, energy and entropy connecting TTC with TS.

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### 5. Results of studying the idealized thermal manufacturing complex of sugar production

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#### 5. 1. Principles and boundaries of idealization of actual technological and energy processes

Taking into consideration that the minimum possible magnitude of pumping cannot be less than the amount of

cell juice, we accept its magnitude as equal to 95 % to m.b. Then we obtain from the material balance of the diffusion separation: the diffusion power supply is provided by water squeezed from pomace in the amount of 63 % to m. b. and excess condensates in the amount of 14.3 % to m.b.; the amount of pressed pomace will be 19.3 % to m.b. Since it is accepted that there are no heat losses in the HS, the temperature of pomace is taken equal to the temperature of the diffusion process – 72 °C.

Similarly, idealizing the processes of heat and mass transfer in diffusion, we assume that the temperature of diffusion juice at the outlet of the diffusion apparatus is equal to the temperature of cossettes.

There are no heat losses through the walls of equipment and pipelines in the juice cleaning department. There are only heat losses associated with the saturation process (calculated according to the procedure [9]). We accept lime consumption for cleaning in the amount of 1 % to m. b.

The amount of excess condensates at the outlet from the TTC is determined from the general production water balance of an enterprise in accordance with the procedure [6] and is 54.9 % to m.b. Obviously, such a system should include multi-stage heating of diffusion juice with maximum use of condensate potentials and secondary steam of vacuum apparatuses in heat exchangers with an efficiency factor equal to unity..

Since the amount of heating of diffusion juice depends on the amount of evaporated water in vacuum apparatuses of crystallizations 1–3, its amount will be determined, observing the idealization conditions. Technological calculation of product separation was carried out at the highest concentration of the DM of syrup, which is used in practice (Denmark) – 78 % DM. Moreover, it was believed that additional vacuum crystallization is used during crystallization 1, which makes it possible to ensure the yield of sugar of 60.15 % to the mass of massecuite. It was also assumed that there are no juice or water dilution when boiling massecuite, and oversaturation of inter crystal solution at the end of boiling is equal to unity. Under these conditions, it will be evaporated in % to m. b:

- 1) crystallization – 3.7;
- 2) crystallization – 0.65;
- 3) crystallization – 0.20.

Total amount of massecuite steam is 4.56 % to m. b.

Temperature of massecuite steam will be accepted as 60 °C, which, taking into consideration technological limitations, meets the condition of minimization of irreversible energy transformations in vacuum apparatuses (only physical and chemical and hydro-dynamic depressions have influence).

Using the procedure [10], the idealized TS, according to the above determined consumption and temperature characteristics, will be depicted in the form of a multi-segment heat exchanger in temperature-enthalpy coordinates (Fig. 1).

As one can see, in heating group 1, we have an excess of condensates heat, and that is why complete temperature alignment does not occur. In this case, the measure of irreversibility of this part of TS will be determined by the technological features of the diffusion process. Fig. 1 shows the results of calculations of temperature of excess condensates at the outlet of TTC for the range of change in temperature of diffusion juice separation, which can be observed when the temperature of the HS (cossettes) changes.

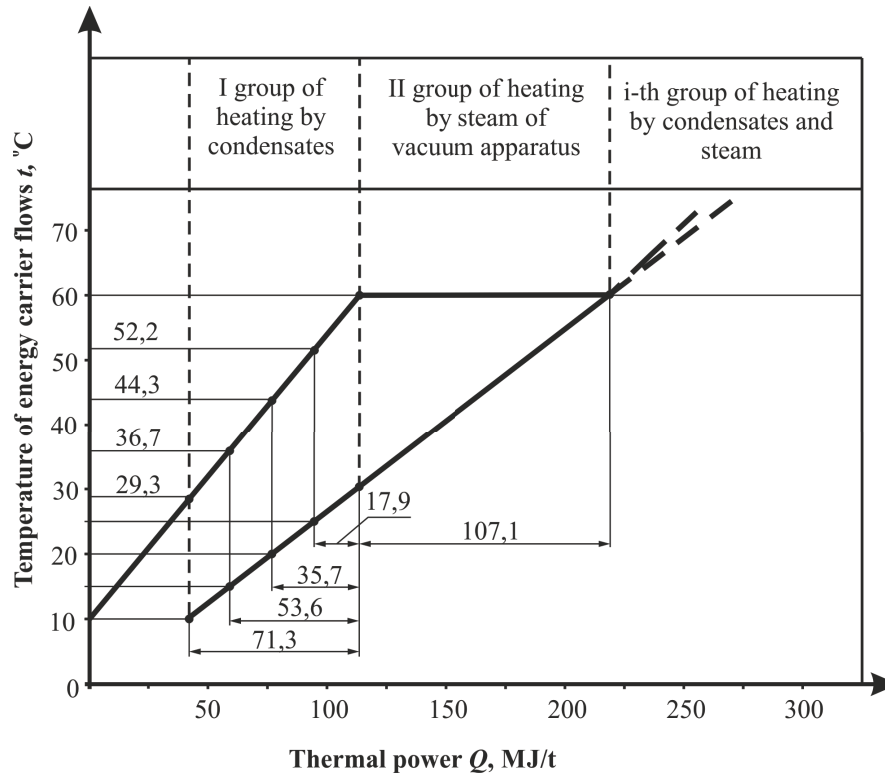


Fig. 1. Idealized heat exchange system of recuperation of heat of secondary energy resources

The following characteristics of other energy carriers will be accepted:

- amount of condensates returning to the TEC with a temperature of 105 °C will be considered equal to the amount of steam entering the plant;
- the amount of electricity used for the technological needs of the TTC will be accepted at the level of the best world indicators – 15 kWh/t b., 50 % of which, due to dissipative phenomena, transfers into internal energy of technological flows.

**5.2. Comprehensive analysis of idealized thermal manufacturing complex of sugar production**

Consider the variant of the idealized TTC with a temperature of cosettes at the inlet to the enterprise equal to 10 °C. The results of preliminary calculations, as well as the data from other technological flows (taken from [11] for the case of processing high quality beets) are summarized in Tables 2–5 according to [12].

In particular, enter material and energy flows that arrive at an idealized TTC in Table 2.

Table 2

Profit component of energy general production synthetic balance (GSB) of idealized TTC

No. by order	Product	Designation	Amount, kg/t	Temperature, °C	DM, %	Flow enthalpy, kJ/t
1	Chips	$G_{ch}$	1,000	10	25	36,140
2	Steam for production	$D_s$	$D_s$	–	–	$H_s(D_s)$
3	Electric energy	$E_{el}$	–	–	–	27,000

Table 3 shows all material and energy flows emanating from the idealized TTC.

Table 3

Consumption component of energy GSB of the idealized TTC

1	Condensate B TEC	$W_{con}$	$\Sigma D_s$	105	–	$H_{con}(D_s)$
2	Excess water	$W_{ex}$	549	29.3	–	67,427
3	Pulp	$G_p$	193	72	32	49,854
4	Molasses	$G_m$	34.34	70	82.5	5,019
5	White sugar	$G_s$	143.64	70	100	14,198
6	Filtration sediment	$G_{fs}$	80	80	50	19,200
7	Water losses in saturations	$W_{sat}$	10	–	–	25,842

Substitute the values from Table 3 in the equation of energy GSB:

$$H_s(D_s) + H_{ch} + E_{el} = H_{con}(D_s) + H_{ex}(W_{ex}) + H_p + H_m + H_s + H_{fs} + H_{sat}, \tag{1}$$

after solving which, we obtain the following data:

- amount of steam that enters the idealized TTC – 52 kg/t;
- minimal possible heat consumption for implementation of technological processes of sugar production by the classic manufacturing circuit – 118.4 MJ/t.

Similar operations will also be performed with entropy characteristics in accordance with procedure [12]. To do this, enter the incoming entropy flows in Table 4, and outgoing enthalpy and entropy flows at appropriate temperatures and at the temperature  $HS$  in Table 5.

**Table 4**  
Profit component of entropy general production balances of idealized TTC

No. by order	Product	Amount, kg/t	Temperature ( $T_i$ ), °C	Flow entropy, kJ/(t·K)	
				Designation	$S_i(T_i)$
1	Chips	1,000	10	$S_{ch}$	129.94
3	Steam	52	130	$\Sigma S_s$	364.67

**Table 5**  
Consumption component of entropy general production balances of idealized TTC

No. by order	Product	Amount, kg/t	Temperature, °C	Flow enthalpy, kJ/t			Flow entropy, kJ/(t·K)		
				Des.	$H_i(t_i)$	$H_i(t_0)$	Des.	$S_i(T_i)$	$S_i(T_0)$
1	Condensate in TPP	52	105	$H_{con}$	22,847	–	$S_{con}$	70.75	–
2	Excess water	549	29,3	$H_{ex}$	67,427	23,069	$S_{ex}$	234.5	82.95
3	Pulp	193	72	$H_p$	49,854	5,479	$S_p$	141.6	19.26
4	Molasses	34,34	70	$H_m$	5,019	626	$S_m$	16.36	2.25
5	White sugar	143,6	70	$H_s$	14,198	1,721	$S_s$	46.27	6.19
6	Filtration sediment	80	80	$H_{fs}$	19,200	2,400	$S_{fs}$	61.65	8.63
7	Losses of water for saturations	10	–	$H_{sat}$	25,842	420	$S_{sat}$	81.45	1.51
8	«Losses» of electricity un TCM	–	–	$Q_{0el}^{in}$	27,000	–	$S_{0el}^{in}$	95.36	–
9	Thermal interaction of TTC with HS	–	–	$\Sigma Q_0$	174,824	–	$\Sigma S_0$	617.4	–

To determine the minimum entropy characteristics, we will write down the following balances:

– entropy general analytical balance:

$$\Sigma S_s + S_{ch} + \Sigma \Delta S_{irrev}^{tot} = S_{con}(T_{con}) + S_{ex}(T_0) + S_{sat}(T_0) + S_s(T_0) + S_p(T_0) + S_m(T_0) + S_{fs}(T_0) + \Sigma S_0; \tag{2}$$

– entropy balance of the TTC subsystem:

$$\Sigma S_s + S_{ch} + \Sigma \Delta S_{irrev}^{in} = S_{con}(T_{con}) + S_{ex}(T_{ex}) + S_{sat}(T_{sat}) + S_s(T_s) + S_p(T_p) + S_m(T_m) + S_{fs}(T_{fs}) + \Sigma S_{0el}^{in}; \tag{3}$$

– entropy balance of conditional subsystem of external irreversibility:

$$S_{ex}(T_{ex}) + S_{sat}(T_{sat}) + S_s(T_s) + S_p(T_p) + S_m(T_m) + S_{fs}(T_{fs}) + \Sigma S_{0el}^{in} + \Sigma \Delta S_{irrev}^{out} = S_{ex}(T_0) + S_{sat}(T_0) + S_s(T_0) + S_p(T_0) + S_m(T_0) + S_{fs}(T_0) + \Sigma S_0. \tag{4}$$

After substituting the corresponding values from Tables 4, 5 in equations (2) to (4), we calculate the following absolute characteristics of the irreversible idealized TTC:

– “minimum” general increase in entropy

$$\Sigma \Delta S_{min}^{tot} = 314.68 \text{ kJ}/(\text{t}\cdot\text{K});$$

– “minimum” increase in entropy from internal irreversibility

$$\Sigma \Delta S_{min}^{in} = 157.94 \text{ kJ}/(\text{t}\cdot\text{K});$$

– “minimum” increase in entropy from external irreversibility

$$\Sigma \Delta S_{min}^{out} = 156.74 \text{ kJ}/(\text{t}\cdot\text{K}).$$

The minimum comprehensive magnitude of specific consumption of conventional fuel will consist of the amount of minimum specific fuel consumption for heat production for technological needs, for electricity production and for the production of lime and saturation gas:

$$B_{min}^{tot} = B_{min}^Q + B_{min}^{el} + B_{min}^{CaO}. \tag{5}$$

Accept that in TTC, thermal processes are also approaching ideal ones: the efficiency of steam generators is 96 % and it is determined by losses with flue gases, heat losses with backwash are 1 %. In the absence of other losses, specific consumption of conditional fuel for heat production will be equal to 36 g c.f./MJ. Then the minimum specific consumption of conditional fuel for heat production for technological needs will be 0.43 % to m.b.

Other minimum consumption of conventional fuel will be accepted according to the data in Table 1 for a potentially possible level, in particular: consumption of conditional fuel for electricity production – 0.23 % m. b.; consumption of conventional fuel for lime production – 0.14 % to m. b.

In this case, according to equation (5), the comprehensive minimum possible consumption of conditional fuel (for the temperature of cosettes of 10 °C) will be equal to 0.8 % m. b.

According to the “principle of energy compensation of irreversibility” [12], the amount of conditional fuel spent on compensation of internal and external irreversibility of the idealized TTC is calculated from the following equations:

$$B_{min}^{in} = b_{min}^{irrev} \cdot \Sigma \Delta S_{min}^{in}, \tag{6}$$

$$B_{min}^{out} = b_{min}^{irrev} \cdot \Sigma \Delta S_{min}^{out}, \tag{7}$$

where  $b_{min}^{irrev} = 13.6 \frac{\text{g}\cdot\text{K}}{\text{kJ}}$  is the minimal specific consumption of conditional fuel to compensate irreversibility of the TTC processes at the temperature of environment (cosettes) of 10 °C [12].

For the purpose of comparative analysis using minimal possible fuel consumption, we studied the influence of cos-

ettes temperature on minimal energy characteristics in the range from 10 °C to 25 °C.

The results are shown in the form of Table 6.

The data of Table 6 show that the effect of temperature of cosettes on energy characteristics of the idealized TTC is minimal, and therefore, the values that correspond to average temperature of chips during the production season can be taken for analysis.

Table 6

Dependence of minimum possible energy characteristics of the thermal manufacturing complex on the temperature of cosettes

No. by order	Indicators	Designation	Temperature of cosettes, °C			
			10	15	20	25
1	Minimum possible comprehensive consumption of c.f., % to m.b.	$B_{min}^{tot}$	0.8	0.792	0.79	0.789
2	Minimum possible consumption of c.f. for heat production for manufacturing needs, % to m.b.	$B_{min}^Q$	0.43	0.422	0.42	0.419
3	Minimum possible consumption of c.f. for compensation of internal irreversibility, % to m.b.	$B_{min}^{in}$	0.22	0.214	0.214	0.214
4	Minimum possible consumption of c.f. for compensation of external irreversibility, % to m.b.	$B_{min}^{out}$	0.21	0.208	0.206	0.205

**5. 3. Criteria of energy efficiency of the thermal manufacturing complex of sugar production**

At this stage, following the strategy of the set problem, we can formulate the content of energy efficiency criteria. Thus, energy efficiency of an arbitrary TTC as the whole or its components, internal and external structures can be evaluated by comparing their energy characteristics with the corresponding characteristics of the idealized complex.

In other words, consider the following coefficients:

– coefficient of total energy efficiency of TTC

$$\phi_B^{tot} = \frac{B_{min}^{tot}}{B_{real}^{tot}}, \tag{8}$$

where  $B_{real}^{tot}$  is the comprehensive consumption of conditional fuel at the operating enterprise, % to m.b.;

– coefficient of energy efficiency of heat supply system of technological processes

$$\phi_B^Q = \frac{B_{min}^Q}{B_{real}^Q}, \tag{9}$$

where  $B_{real}^{tot}$  is the consumption of conditional fuel for heat production for manufacturing needs of an operating enterprise, % to m.b.;

– coefficient of energy efficiency of internal structure of the TTC

$$\phi_B^{in} = \frac{B_{min}^{in}}{B_{real}^{in}}, \tag{10}$$

where  $B_{real}^{in}$  is the consumption of conditional fuel for compensation of internal irreversibility of an operating enterprise, % to m. b.;

– coefficient of energy efficiency of external structure of the TTC

$$\phi_B^{out} = \frac{B_{min}^{out}}{B_{real}^{out}}, \tag{11}$$

where  $B_{real}^{out}$  is the consumption of conditional fuel for compensation of external irreversibility of an operating enterprise, % to m. b.

**5. 4. Approbation of criteria on the example of analysis of measures to increase the energy efficiency of a sugar enterprise**

Illustrate the use of the procedure for analyzing energy efficiency of the TTC to analyze the phased implementation of a preliminarily developed comprehensive system of measures. For calculations, we will accept the source data of a sugar factory of the simplest configuration, given in publication [12]. Consider the main four stages.

*Stage 1 – return of “ammonia” condensates to power a diffusion unit.*

In order to reduce heating of water entering the plant in the form of so-called “barometric” water and leaving it in the form of so-called “ammonia” condensates, all ammonia condensates are returned to power the diffusion unit, i.e.  $W_{ex}=0$ . The temperature of ammonia condensates becomes unimportant, so cooling ammonia condensates in this case is a technological measure.

*Stage 2 – return of water squeezed from pomace to power the diffusion apparatus.*

In the diffusion department, one transfers to the diffusion-press method of juice extracting, for which pomace deep-presses (in pressed pomace  $DM=25\%$ ) are installed, and all water squeezed from pomace returns to power the diffusion apparatus. Other amount of water for power supply arrives in the form of ammonia condensates.

*Stage 3 – an increase in contents of dry matter of the product before vacuum apparatuses.*

Vacuum apparatuses with mechanical circulators are installed in the product (crystallization) compartment, which makes it possible to boil thick products. For calculations, we will take the value of dry matter in the syrup mixture after the evaporation installation and melt liquor entering the vacuum apparatuses 1 of product, 72 %.

*Stage 4 – use of massecuite steam to heat diffusion juice.*

When switching to power supply of the diffusion unit with water squeezed from pomace and ammonia condensate, the option of heat recuperating of the massecuite steam for preheating barometer water is over. Partially, this secondary energy can be used to heat diffusion juice. Consider the option of heating diffusion juice by 20 °C.

The main results of calculations are summarized in Tables 7, 8.

The obtained results make it possible to draw unambiguous conclusions about the effectiveness of the implementation of a particular measure.

**Table 7**  
Results of analysis of influence of certain factors on heat usage efficiency

No. of entry	Indicator	Basic variant	Stage 1	Stage 2	Stage 3	Stage 4
1	Consumption of barometric water, kg/t	930	219.2	0	0	0
2	Consumption of excess water, kg/t	711	0	362	397.4	433.7
3	Consumption of steam for manufacturing needs, kg/t	342.8	310.1	299.6	264.3	229.5
4	Consumption of heat for manufacturing needs, MJ/t	781.4	707.1	683.1	602.6	523.3
5	Production of electricity on thermal consumption, kW·h/t	30	30	30	28.4	24.6
6	Consumption of conditional fuel for manufacturing needs, m <sup>3</sup> /t	29.6	26.8	25.9	22.8	19.8
7	Consumption of conditional fuel for electricity generation, kg/t	4.5	4.5	4.5	4.3	3.7
8	Consumption of conditional fuel for manufacturing and electricity generation, kg/t	34.1	31.3	30.4	27.1	23.5
9	Comprehensive consumption of gas, m <sup>3</sup> /t	30.47	27.97	27.17	24.22	21
10	Share of thermal consumption in total heat consumption, %	21.4	23.7	24.5	27.8	32
11	Relative decrease in heat consumption for technological needs, %	–	9.5	12.6	23	33

**6. Discussion of the results of the study of procedure for analysis of effectiveness of the use of fuel and energy resources in sugar production**

Idealization of thermal manufacturing processes by minimizing irreversibility allowed calculating the boundary energy and entropy characteristics of a modern sugar production TTC. In particular, the comprehensive minimum possible consumption of conditional fuel  $B_{min}^{tot} = 0.8\%$  to m. b. and the “minimum” total increase in entropy  $\sum \Delta S_{min}^{tot} = 314.68 \text{ kJ}/(\text{t} \cdot \text{K})$ , which today can be considered the basis for quantitative assessment of the perfection level of existing and alternative thermal circuits, was determined. It is worth noting that only 54 % (0.43 % to m. b.) of the total minimum possible consumption of conditional fuel is spent to produce heat for manufacturing needs, and the rest are consumptions for electricity and lime production (Table 6).

In accordance with the principle of “energy compensation of irreversibility”, the consumption of conditional fuel to compensate for the internal and external irreversibility of an idealized TTC were calculated in quantities:  $B_{min}^m = 0.22\%$  to m.b. and  $B_{min}^{out} = 0.21\%$  to m.b. (Table 6). Given that  $B_{min}^{out}$  is 49 % of  $B_{min}^m$ , we can assume the potential possibility to reduce the minimum fuel consumption for technological needs by minimizing external irreversibility. The latter can be achieved only if reversible heat pump systems are used. However, this issue was not considered, as the task was to explore the boundary characteristics of the classical circuit. Obviously, in the long run it is worth considering, as heat pump systems are becoming increasingly popular.

The developed efficiency criteria showed good results. Tables 7, 8 showed that stage-by-stage implementation of measures to increase the efficiency of sugar production leads to a consistent reduction in complex fuel consumption. We can also simultaneously observe the positive dynamics of coefficients: of total energy efficiency of the TTC  $\phi_B^{tot}$ , of energy efficiency of the internal structure of the TTC  $\phi_B^m$  and energy efficiency of the external structure of the TTC  $\phi_B^{out}$ . However, despite the comprehensive generally accepted system of measures, the level of perfection of the classic thermal manufacturing circuit was raised only up to 34 %, which indicates a great potential for optimization of energy use at sugar enterprises.

**Table 8**  
Results of analysis of the impact of certain factors on energy efficiency and the T TTC MC imperfection

No. by order	Indicator	Basic variant	Stage 1	Stage 2	Stage 3	Stage 4
1	Total increase in entropy from irreversibility of processes in the TTC, kJ/(t·K)	1,203	1,122.3	1,099	994	863.4
2	Increase in entropy from internal irreversibility of the TTC, kJ/(t·K)	437.5	354	386.3	346.3	299.4
3	Increase in entropy from external irreversibility of the TTC, kJ/(t·K)	765.5	768.3	712.7	647.7	564
4	Increase in entropy from irreversibility of thermal interaction, kJ/(t·K)	821.6	740.9	717.6	632.9	550.4
5	Increase in entropy from dissipation of electricity, kJ/(t·K)	381.4	381.4	381.4	361.1	313
6	Specific consumption of conditional fuel for compensation of irreversibility, (g·K)/kJ	28.3	27.89	27.66	27.27	27.28
7	Consumption of conditional fuel for compensation of internal irreversibility, kg/t	12.4	9.9	10.7	9.4	8.1
8	Consumption of conditional fuel for compensation of external irreversibility, kg/t	21.7	21.4	19.7	17.7	15.4
9	Consumption of conditional fuel for compensation of total irreversibility, kg/t	34.1	31.3	30.4	27.1	23.5
10	Coefficient of total energy efficiency of the TTC, %	23.5	25.6	26.3	29.5	34.04
11	Coefficient of energy efficiency of internal structure of the TTC, %	17.7	22.2	20.6	23.4	27.2
12	Coefficient of energy efficiency of external structure of the TTC, %	9.7	9.8	10.7	11.9	13.6

Under these conditions, the logical continuation of this work may be the development and analysis of new technological, technical and structural measures in order to bring the actual energy characteristics of enterprises closer to idealized ones.

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## 7. Conclusions

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1. By idealizing technological and energy processes, a hypothetical sugar-producing TTC was synthesized, which implies maximum possible alignment of temperatures and concentrations, minimal dissipation of mechanical energy, as well as the absence of “losses” of heat into the environment. Obviously, such TTC can be considered exemplary for the classical technology of sugar production.

2. Comprehensive analysis of the idealized TTC resulted in determining key reference characteristics for modern enterprises of the sugar industry. In particular, the minimum possible heat consumption for the implementation of technological processes of sugar production was calculated – 118.40 MJ/t; “minimum” total increase in entropy from irreversible processes of the TTC – 314.68 kJ/(t·K);

minimum comprehensive magnitude of specific consumption of conditional fuel – 0,8 % to m. b.

3. New criteria for energy efficiency of the sugar production TTC were developed, including: coefficient of total energy efficiency of the TTC, coefficient of energy efficiency of the heat supply system of technological processes and coefficients of energy efficiency of internal and external structures of the TTC. Taking into consideration that these criteria are based on minimal characteristics of the exemplary TTC, they make it possible to objectively quantify the level of perfection of the existing and the proposed thermal circuits, as well as the impact of both separate measures to increase energy efficiency and their complex on their perfection.

4. The application of the developed criteria for analysis of step-by-step implementation of classical measures to increase energy efficiency of a sugar enterprise showed that energy efficiency of most sugar plants does not exceed 35 %, and that of the best world samples reaches only 45 %. Obviously, such a low result indicates that the introduction of resource-saving measures based on scientifically grounded principles can have a significant impact on the enhancement of economic performance of enterprises.

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