

Представлено апробацію методики термодинамічного аналізу теплотехнологічного комплексу цукрового виробництва на прикладі аналізу підприємства типової конфігурації.

На сьогодні термодинамічний аналіз систем цукрового виробництва переважно реалізований на основі класичного енергетичного методу. Незначні спроби використати потенціал другого закону термодинаміки у вигляді адаптації ексергетичного методу не набули системного характеру.

В основі застосованої методики спільний аналіз загальних синтетичних і аналітичних балансів маси, енергії та ентропії. Така методика дозволяє кількісно оцінювати рівень досконалості існуючих та пропонує теплових схем. Також вплив на їх досконалість заходів з підвищення енергетичної ефективності і може бути застосована як для оптимізації енергетичних характеристик діючих, так і під час проектування нових підприємств цукрової промисловості.

Показано, що термодинамічний аналіз теплотехнологічного комплексу цукрового виробництва як єдиної системи дозволяє аналізувати основні фактори впливу на енергетичну ефективність комплексу безвідносно до перебігу процесів, що реалізуються в ньому. Такий підхід також можна ефективно використовувати для швидкої оцінки термодинамічної досконалості підприємства та визначення його «енергозберігаючого потенціалу».

За результатами енергетичного аналізу встановлено взаємозв'язки між підведеними до системи паливно-енергетичними ресурсами та джерелами їх втрат і запропоновано комплекс заходів зі зменшення впливу кожного з цих факторів на витрату ресурсів.

Ентропійний аналіз виявив внутрішні та зовнішні причини необоротності процесів, а принцип «енергетичної компенсації необоротності» дозволив скласти рейтинг основних недосконалостей і визначити оптимальну послідовність реалізації ресурсозберіжних заходів.

Результати аналізу підтвердили ефективність методики, що забезпечує комплексне дослідження, оперуючи лише фундаментальними законами та принципами класичної термодинаміки на відміну від методик, в основі яких енергетично-ексергетичні характеристики

Ключові слова: цукрове виробництво, термодинамічний аналіз, ентропійний метод, енергетична ефективність, ресурсозберіжні заходи

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THERMODYNAMIC ANALYSIS OF THE THERMAL-TECHNOLOGICAL COMPLEX OF SUGAR PRODUCTION: THE ENERGY AND ENTROPY CHARACTERISTICS OF AN ENTERPRISE

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1. Introduction

Higher fuel prices and stricter environmental standards require the intensive introduction of energy- and resource-saving technologies, including sugar production. The main methodological issue in resolving this task is the absence of a single comprehensive technique for analyzing and optimizing the energy efficiency of a thermal-technological complex (TTC) of sugar production. The modern thermodynamic analysis requires not only determining the aggregate

absolute energy characteristics of the complex operation but also applying the comprehensive criteria that would uniquely characterize those energy transformations that occur in the thermodynamic systems of sugar production [1]. It is important that such criteria are scientifically justified and conform to the fundamental principles of a general optimization methodology for heat exchange processes and systems.

Therefore, it is a relevant task to develop a comprehensive tool of thermodynamic analysis and optimization of sugar production TTC, which would make it possible for an

engineer to resolve complex tasks when implementing innovative energy- and resource-saving technologies.

2. Literature review and problem statement

Among methods of the analysis, synthesis, and optimization of chemical and technological systems, an important role belongs to the methods of thermodynamic analysis. In particular, the feasibility of the use of thermodynamics for the optimization of the energy characteristics of systems was justified in [2]; the need for a joint application of the first and second laws of thermodynamics was emphasized. The author explains that any energy-technological system implements the irreversible energy transformations, whose measure of the irreversibility determines its energy efficiency. However, the cited publication does not provide a mechanism for the practical implementation of thermodynamic analysis.

Paper [3] gives the analytical review of the modern methods of thermodynamic analysis, but most of them are represented by the energy and exergy analysis of thermal machines. The authors of studies [4, 5] have successfully investigated alternative technologies for improving the thermodynamic characteristics of the energy-generating systems by using a modern exergetic tool. In addition, exergy analysis is often used to optimize cogeneration and trigeneration systems [6], including in sugar production, shown in [7].

The application of the second law of thermodynamics to the analysis of thermal-technological systems of sugar production is mainly due to borrowing the experience of exergetic analysis of thermal machines [8–10]. In addition, work [11] reports the exergetic analysis of the production processes of raw sugar from sugar cane. It is obvious that earlier studies confirm the necessity of the application of a comprehensive thermodynamic analysis in sugar production. However, paper [12] showed that the exergetic approach significantly complicates the analysis procedure due to the thermodynamically incorrect (in a given case) estimation of the efficiency of thermal processes using the hypothetical loss of serviceability.

The alternative type of thermodynamic analysis based on the second law of thermodynamics is the entropy analysis, one of the variants of which is given in paper [13]. This approach is scientifically grounded in relation to the thermal-technological systems in which the dominant form of energy interaction is thermal, rather than mechanical. However, the cited paper reports an entropy study of a separate heat exchanger only. That is, the issue of systems analysis remained unresolved.

Article [1] describes a procedure of the thermodynamic analysis of a sugar production TTC, based on a joint analysis of general synthetic and analytical balances of mass, energy, and entropy. The authors believe that the devised procedure makes it possible to analyze the main factors influencing the energy efficiency of the complex without regard to the course of processes implemented within the system, as well as to determine the sources and causes of systems imperfection.

Thus, the results of our analysis of the scientific literature allow us to draw a conclusion about the need for a comprehensive thermodynamic analysis of the effectiveness of a sugar production TTC; however, the practical implementation of this task should be performed on the basis of the energy and entropy characteristics and relevant effectiveness criteria.

3. The aim and objectives of the study

The aim of this study is the approbation of a procedure for TTC thermodynamic analysis based on the general energy and entropy balances of the complex. This could enable the practical identification of ways to improve the energy efficiency of enterprises.

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

- to perform a general energy analysis of the sugar production TTC and formulate the basic stages of energy efficiency improvement;
- to perform a general entropy analysis of the sugar production TTC and devise additional stages of energy efficiency improvement.

4. Materials and methods of thermodynamic analysis of the thermal-technological complex of sugar production

We shall show the peculiarities of the application of the developed procedure of thermodynamic analysis of sugar production TTC [1] using an example of the analysis of a sugar factory of typical configuration.

The following data are accepted in our calculation:

- digestion of beets – 17 %;
- the type of diffusion installation – inclined screw-type;
- the juice extraction method is purely diffusive without the use of pulp press water;
- pumping out a diffusion juice – $G_{dj}=1,100$ kg/t of beet;
- the purity of a diffusion juice – 90 %;
- the solids content in the pulp – 7.5 %;
- electric energy consumption for technological needs – 30 kW·h/t.

Characteristics of the thermal-technological scheme:

- supply of the diffusion plant – barometric water;
- the secondary vapor of vacuum machines is used only for heating the barometric water within the vacuum-condensing unit;
- the temperature of barometric water before the vacuum-condensing unit – 10 °C, after – 45 °C;
- vacuum devices – with immediate circulation.

At present, all material flows and energy losses into the environment at certain stages of the technological process are examined for the thermal-technological scheme of a sugar factory of typical configuration and determined according to [14] for the case of high-quality beet processing.

The flow rate of barometric water and pulp is determined from the balance calculation of the sloping screw-type diffusion installation (DI): pulp consumption $G_p=830$ kg/t; the consumption of barometric water at DI $W_{bw}=930$ kg/t; pulp temperature – 70 °C.

The consumption by the secondary pair of vacuum devices («massecuite vapor»), supplied to the vacuum condensing unit, is determined from the material water balance of the product department from formula 1, taking into consideration:

- the amount of syrup supplied $G_{syr}=253$ kg/t with $DS_{syr}=65$ %;
- the amount of remelt syrup supplied $G_{rss}=125$ kg/t with $DS_{rss}=65$ %;
- the amount of water for clarification $W_{cl}=9.43$ kg/t;
- the amount of molasses leaving the product department $G_m=34.32$ kg/t with $DS_m=82.5$ %:

$$D_{mv} = G_{syr}(1 - DS_{syr}) + G_{rss}(1 - DS_{rss}) + W_{cl} - G_m(1 - DS_m) = 134.27 \text{ kg/t.} \quad (1)$$

To determine the amount of barometric water supplied to the TTC (capacitor) (W_{bw}^{in}) and the amount of massecuite vapor, which leaves it (D_{mv}^{out}), we build and solve the following system of equations:

$$W_{bw} = W_{bw}^{in} + D_{mv}^{con}, \quad (2)$$

$$D_{mv}^{con} = (H_{bw}^{out}(W_{bw}, 45^\circ\text{C}) - H_{bw}^{in}(W_{bw}^{in}, 10^\circ\text{C})) / r_{mv}, \quad (3)$$

$$D_{mv}^{out} = D_{mv} - D_{mv}^{con}, \quad (4)$$

where D_{mv}^a is the amount of massecuite vapor, which condenses on the barometric water.

As a result, we obtain $W_{bw}^{in} = 877.4 \text{ kg/t}$, $D_{mv}^{con} = 52.6 \text{ kg/t}$, $D_{mv}^{out} = 81.67 \text{ kg/t}$.

It is obvious that we consider an idealized approximate scheme, in which we neglect the magnitude of vapor flow rate for the evaporation of juice and water additional supplies; all other additional vapor consumption is included in a relatively small value of D_{pr} .

The value of energy losses into the environment is assigned by the natural expression of the amount of vapor entering the factory to compensate for these losses: at the product department $D_{pr} = 15 \text{ kg/t}$. Additional normalized consumption of vapor: to dry sugar, $D_{ds} = 10 \text{ kg/t}$; for heating

the syrup and remelt syrup – $D_{sr} = 10 \text{ kg/t}$. Other overall losses, $D_{other} = 20 \text{ kg/t}$.

Energy losses into the environment at a juice purifying department: according to the recommendations from [14], at processing the high-quality beet, for $G_{dj} = 1,100 \text{ kg/t}$, the juice, during saturation hour 1, is cooled by 4°C , during saturation hour 2, by 2°C . While filtering and subsequent processes – additionally, by 4°C . In the natural representation of the amount of technological vapor, it would equal, additionally, to about $D_{dj} = 22 \text{ kg/t}$.

That is, the total loss of energy into the environment in the natural equivalent would equal:

$$\sum D_0^v = D_{pr} + D_{dj} + D_{other} + D_{ds} + D_{sr} = 15 + 22 + 20 + 10 + 10 = 77 \text{ kg/t;} \quad (5)$$

in the form of heat –

$$Q_0^v = \sum D_0^v (h_v'' - h_v') = 77(2720 - 546) = 167.375 \text{ MJ/t.} \quad (6)$$

The calculations were performed using the standard Microsoft Office and Mathcad software packages.

5. Results of the thermodynamic analysis of a thermal-technological complex of sugar production

5.1. Determining basic energy characteristics

In the first stage, we enter items related to the material and energy general balances (GB) into Tables 1, 2.

Table 1

Profitable component of the energy general synthetic balance

No. of entry	Product	Designation	Amount, kg/t	Temperature, °C	DS, %	Flow enthalpy, kJ/t
1	Chips	G_{chips}	1,000	10	25	36,140
2	Barometric water	W_{bw}^{in}	877.4	10	–	36,868
3	Overall compensation for the losses in TTC	$\sum D_0^v$	77	–	–	–
4	Vapor for technology	D_v	D_v	–	–	$H_v(D_v)$
5	Electrical energy	E_{el}		–	–	108,000

Table 2

Cost component of energy GSB

No. of entry	Product	Designation	Amount, kg/t	Temperature, °C	DS, %	Flow enthalpy, kJ/t
1	Condensate in TPS	W_{con}	$\sum D_v$	105	–	$H_{con}(D_v)$
2	Excess water	W_{exc}	$W_{нал}$	t_{exc}	–	$H_{exc}(W_{exc})$
3	Pulp	G_p	830	70	7.5	235,861
4	Secondary vapor of vacuum devices	D_{mv}^{out}	81.67	72	–	214,686
5	Molasses	G_m	34.34	70	82.5	5,047
6	White sugar	G_s	143.64	70	100	10,510
7	Filtration sediment	G_{fs}	100	80	50	24,000
8	Water losses at saturation	W_{sat}	11	–	–	28,426
9	Heat «losses» at TTC	$\sum Q_0^m$	–	–	–	167,375 + 0.6·108,000

According to the procedure given in [1], we build an equation of GB, taking into consideration a series of simplifications:

- the amount of condensate returned to TPS equals the technological vapor consumption by a plant from TPS, that is, $W_{con}=\Sigma D_v$;
 - given the relatively small values and in order to simplify the calculations, we exclude from the balances lime, saturation gas, and the energy of exothermic reaction;
 - the energy cost for heating air to dry sugar is accounted for in D_{ds} ;
 - at the dissipation of electric energy, 40 % converts into the internal energy of the flows, the rest are the «losses».
- The overall water balance equation of a factory:

$$D_v + \sum D_0^v + W_{bw}^{in} + G_{chips} (1 - DS_{chips}) = D_{mv}^{out} + W_{com} (D_v) + W_{exc} + W_{sat} + G_p (1 - DS_p) + G_m (1 - DS_m) + G_{fs} (1 - DS_{fs}). \tag{7}$$

The equation of energy GSB:

$$H_v (D_v + \sum D_0^v) + H_{chips} + H_{bw} + E_{el} = H_{con} (D_v + \sum D_0^v) + H_{exc} (W_{exc}) + H_{mv}^{out} + H_p + H_m + H_{fs} + H_s + \sum Q_0^{in}. \tag{8}$$

Next, by substituting into the system of equations (7), (8) the corresponding values of magnitudes from Tables 1, 2, and by solving it, we obtain the following characteristics:

- the amount of water that is discharged from a factory in the form of ammonia condensates, $W_{exc}=711$ kg/t;
- the amount of vapor, which enters a factory, except for the vapor used to compensate for losses (at a temperature of ammonia condensate after cooling in a heat exchanger of

$t_{exc}=70$ °C), $D_v= 265.8$ kg/t; the total vapor consumption for technological needs would equal $\Sigma D_v=342.8$ kg/t.

Based on preliminary data, we calculate a set of absolute energy indicators.

Heat consumption for technological needs:

$$Q_{tech} = 781.43 \text{ MJ/t} = 186.64 \text{ Mcal/t}. \tag{9}$$

The consumption of conditional fuel on the production of technological vapor in TPS:

$$B_{tech}^Q = Q_{tech} / (Q_n^r \eta_{TPS}^Q) = 781430 / (29330 \cdot 0.9) = 29.6 \text{ kg/t}. \tag{10}$$

At the electric energy consumption for technological needs of 30 kW·h/t, we obtain the consumption of conditional fuel for electricity generation:

$$B_{tech}^{el} = 30 \cdot 3600 / (Q_n^r \eta_{TPS}^{el}) = 108000 / (29330 \cdot 0.82) = 4.49 \text{ kg/t}. \tag{11}$$

Conditional fuel consumption for technological needs and power generation:

$$B = B_{tech}^Q + B_{tech}^{el} = 34.09 \text{ kg/t}. \tag{12}$$

The total gas consumption would equal 30.47 m³/t.

5. 2. Determining general entropic characteristics

In the second stage, the overall entropy characteristics of TTC are defined, with the corresponding entropy GB. The profitable component of entropy GBs is shown in Table 3; the cost component – in Table 4.

Table 3

The profitable component of entropy GBs

No. of entry	Product	Amount, kg/t	Temperature (T_i), °C	Flow entropy, kJ/(t·K)	
				Designation	$S_i(T_i)$
1	Chips	1,000	10	S_{chips}	129.94
2	Barometric water	877.4	10	S_{bw}	132.56
3	Vapor overall consumption	342.8	130	ΣS_v	2,408.3

Table 4

The cost component of entropy GBs

No. of entry	Product	Amount, kg/t	Temperature, °C	Flow entropy, 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 TPS	342.8	105	H_{con}	150,883	–	S_{con}	467.2	–
2	Excess water	711	70	H_{exc}	208,327	29,876	S_{exc}	679	107.4
3	Pulp	830	70	H_p	235,861	27,681	S_p	685.5	97.6
4	Secondary vapor of vacuum devices	81.67	72	H_{mv}^{out}	214,686	3,431	S_{mc}^{out}	630.7	12.34
5	Molasses	34,34	70	H_m	5,019	626	S_m	16.36	2.25
6	White sugar	143.6	70	H_s	14,198	1,721	S_s	46.27	6.19
7	Filtration sediment	100	80	H_{fs}	24,000	3,000	S_{fs}	77,1	10.8
8	Water losses at saturation	11	–	H_{sat}	28,426	462	S_{sat}	89.6	1.66
9	Heat «losses» in TTC	–	–	ΣQ_0^{in}	232,175		ΣS_0^{in}	576,12	
10	Overall heat «losses»	–	–	ΣQ_0	895,895		ΣS_0	3,166,7	

For a given case, the thermodynamic temperature of the external environment (EE) as the weighted average of the flow of chips and barometric water is $T_0=283.15$ K.

The entropy general analytic balance (GAB) takes the form:

$$\begin{aligned} & \sum S_v + S_{bw} + S_{chips} + \sum \Delta S_{irrev}^{tot} = \\ & = S_{mv}^{out}(T_0) + S_{con}(T_{con}) + S_{exc}(T_0) + \\ & + S_{sat}(T_0) + S_s(T_0) + S_p(T_0) + S_m(T_0) + S_{fs}(T_0) + \sum S_0. \end{aligned} \quad (13)$$

The entropy balance of the TTC subsystem:

$$\begin{aligned} & \sum S_v + S_{bw} + S_{chips} + \sum \Delta S_{irrev}^{in} = \\ & = S_{mv}^{out}(T_{mv}) + S_{con}(T_{con}) + S_{exc}(T_{exc}) + S_{sat}(T_{sat}) + \\ & + S_s(T_s) + S_p(T_p) + S_m(T_m) + S_{fs}(T_{fs}) + \sum S_0^{in}, \end{aligned} \quad (14)$$

The entropy balance of the external irreversibility conditional subsystem (EICS):

$$\begin{aligned} & S_{exc} + S_{sat} + S_s + S_p + S_m + S_{fs} + \sum S_0^{in} + \sum \Delta S_{irrev}^{out} = \\ & = S_{mv}^{out}(T_0) + S_{exc}(T_0) + S_{sat}(T_0) + S_s(T_0) + S_p(T_0) + \\ & + S_m(T_0) + S_{fs}(T_0) + \sum S_0. \end{aligned} \quad (15)$$

Substituting in equation (13) to (15) the corresponding values from Tables 3, 4, we calculate the following absolute characteristics of irreversibility:

– the general growth of entropy in the interaction of TTC with EE:

$$\sum \Delta S_{irrev}^{tot} = 1203 \text{ kJ}/(\text{t}\cdot\text{K});$$

– a growth of entropy due to the internal irreversibility:

$$\sum \Delta S_{irrev}^{in} = 437.5 \text{ kJ}/(\text{t}\cdot\text{K});$$

– a growth of entropy due to the external irreversibility:

$$\sum \Delta S_{irrev}^{out} = 765.5 \text{ kJ}/(\text{t}\cdot\text{K}).$$

Divide the corresponding growth in entropy by the generating sources.

The general growth of entropy due to the dissipation of electric energy:

$$\sum \Delta S_{irrev}^{el} = \frac{E_{tech}^{el}}{T_0} = \frac{30 \cdot 3600}{283.15} = 381.42 \text{ kJ}/(\text{t}\cdot\text{K}). \quad (16)$$

The general growth of entropy due to the irreversibility of thermal interaction:

$$\begin{aligned} \sum \Delta S_{irrev}^Q &= \sum \Delta S_{irrev}^{tot} - \sum \Delta S_{irrev}^{el} = \\ &= 1203 - 381.42 = 821.58 \text{ kJ}/(\text{t}\cdot\text{K}). \end{aligned} \quad (17)$$

At the average weighted temperature of the output flows in a TTC subsystem of $T_m^{out} = 349.7$ K, we shall divide the entropy growth due to the internal and external irreversibility into a thermal and dissipative component:

– the entropy growth due to the dissipation of electric energy within the TTC subsystem:

$$\sum_{in} \Delta S_{irrev}^{el} = \frac{E_{el}^{in}}{T_m^{out}} = \frac{0.4 \cdot 30 \cdot 3600}{349.7} = 123.5 \text{ kJ}/(\text{t}\cdot\text{K}); \quad (18)$$

– the entropy growth due to the thermal interaction inside a TTC subsystem:

$$\begin{aligned} \sum_{in} \Delta S_{irrev}^Q &= \sum \Delta S_{irrev}^{in} - \sum_{in} \Delta S_{irrev}^{el} = \\ &= 437.5 - 123.5 = 314 \text{ kJ}/(\text{t}\cdot\text{K}); \end{aligned} \quad (19)$$

– a growth of entropy due to the dissipation of electrical energy from the outside of the TTC subsystem (in the EICS subsystem):

$$\begin{aligned} \sum_{out} \Delta S_{irrev}^{el} &= \sum \Delta S_{irrev}^{el} - \sum_{in} \Delta S_{irrev}^{el} = \\ &= 381.42 - 123.5 = 257.92 \text{ kJ}/(\text{t}\cdot\text{K}); \end{aligned} \quad (20)$$

– the increased entropy due to the thermal interaction outside a TTC subsystem:

$$\begin{aligned} \sum_{out} \Delta S_{irrev}^Q &= \sum \Delta S_{irrev}^{out} - \sum_{out} \Delta S_{irrev}^{el} = \\ &= 765.5 - 257.92 = 507.58 \text{ kJ}/(\text{t}\cdot\text{K}). \end{aligned} \quad (21)$$

In the third stage, the specific conditional fuel consumption is determined to compensate for the unit of irreversibility. To this end, consider a system A (Fig. 1), in which the fuel energy in the amount $E_x = BQ_n^r$, through the sequence of irreversible energy transformations, enters EE (system C) in the form of heat Q_{Ex} with a temperature of T_0 .

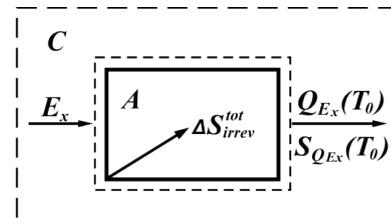


Fig. 1. The scheme of general transformations of fuel energy and entropy at a sugar enterprise

To simplify the calculations, we shall consider the chemical energy of fuel at the initial stage of energy transformations to be an entropy-free form of energy. In this case, the total growth of entropy is calculated from the following equation:

$$\Delta S_{irrev}^{tot} = S_{Q_{Ex}}(T_0). \quad (22)$$

Given that $Q_{Ex}(T_0) = BQ_n^r$, then

$$\Delta S_{irrev}^{tot} = \frac{BQ_n^r}{T_0}. \quad (23)$$

Then, the fuel consumption, which is used to compensate for the unit of an irreversibility of the full sequence of energy transformations, including the stages of transformation of the primary ordered (entropy-free) energy into unordered and bringing the potentials of the latter to the EE parameters, taking into consideration equation (23), is determined as follows:

$$b_{irrev}^{tot} = \frac{B}{\Delta S_{irrev}^{tot}} = \frac{T_0}{Q_n^r}. \quad (24)$$

The balance of the system, which is the consumer of the secondary forms of energy (heat, electric energy), must

include the costs associated with the generation of these energies (for a sugar enterprise, such system is TTC). When analyzing such a system, the equation of calculating the specific consumption of fuel to compensate for the irreversibility is recorded in a different form:

$$b_{irrev} = \frac{b_{irrev}^{tot}}{\omega}, \tag{25}$$

where ω is the relative irreversibility factor of the analyzed system.

For example, for the combined system TPS+TTC, according to the accepted initial data on the preliminary analysis and the calculation results, the specific consumption of conditional fuel to compensate for the irreversibility is:

$$b_{irrev}^{tot} = \frac{T_0}{Q_n} = \frac{283.15}{29330} = 9.65 \frac{\text{g} \cdot \text{K}}{\text{kJ}}. \tag{26}$$

For a separate TTC system as a consumer of heat and electric energy, taking into consideration the value of a relative coefficient of the TTC's irreversibility:

$$\omega_{TTC} = \frac{\sum \Delta S_{irrev}^{tot}}{\Delta S_{max}^{tot}} = \frac{1203}{3531,3} = 0.3407 \tag{27}$$

the specific consumption of conditional fuel to compensate for the irreversibility would obviously increase:

$$b_{irrev} = \frac{b_{irrev}^{tot}}{\omega_{TTC}} = \frac{9.65}{0.3407} = 28.3 \frac{\text{g} \cdot \text{K}}{\text{kJ}}. \tag{28}$$

In equation (27), ΔS_{max}^{tot} is the growth of entropy in the combined system TPS+TTC.

The fourth stage, in accordance with an irreversibility energy compensation principle [1], implies the analysis of the sources of irreversibility as individual fuel consumers and the construction of imperfections ratings.

The results of our analysis are summarized in Table 5, where $B_i = b_{irrev}^{tot} \Delta S_{irrev_i}$ is the fuel consumption to compensate for the i -th irreversibility, ω_i^{out} and ω_i^{tot} are the relative irreversibility coefficients, showing the influence exerted by the i -th flow on the external and overall irreversibility of the TTC, respectively. By analyzing the relevant columns in Table 5, it is possible to draw conclusions about the degree of influence exerted by any flow on the external and the overall irreversibility of the TTC processes, as well as its energy efficiency.

6. Discussion of results of the thermodynamic analysis of a thermal-technological complex of sugar production

6.1. Energy analysis results

It is obvious that the derived value of fuel consumption for the production of technological vapor is close to the limit value (the minimum possible) for those thermal-technological circuits in which heat from the secondary energy resources is used in a limited manner, namely:

- the heat of ammonia condensates is used only for heating products;
- the heat of the massecuite vapor is used only for heating barometric water within a vacuum-condensing unit.

The analysis of the energy GSB equation reveals that the heat at a factory is used for the following:

1. Heating dry solids entering a factory from ambient temperature to the temperature of pulp, sugar, molasses, filtration sludge, respectively. However, since these temperatures are determined by the technological process, the impact on this balance item could be only minimal.
2. Heating the main part of the water entering a factory with beet and nourishing water to the temperature of pulp and the final temperature of ammonia condensate, respectively.
3. The evaporation of the part of the water received by a factory in the amount of vapor coming from the vacuum devices to a vacuum-condensing unit.
4. The compensation for the heat losses into the environment. Even for relatively low loss values, set according to [14], they equal, on average, 27 % of the «direct» energy consumption for the technological process.

Accordingly, one could suggest a set of measures to reduce the impact of each of these factors on the fuel and energy resources (FER) flow rate:

1. Reducing the amount of water entering a factory and, consequently, reducing the amount of ammonia condensates (the amount of water in the pulp is determined by the technological process). This requires:
 - 1.1. The bulk of the water contained in the pulp should be closed inside a factory, by removing it from the pulp using the pulp presses and returning to power the diffusion apparatus. This technological task requires the transition from a pure diffusion procedure of juice extraction to a fundamentally different one – diffusion-pressing.
 - 1.2. The supply of the diffusion unit must also include the returned ammonia condensates, which would exclude one of the components of external irreversibility.

Table 5

Results of entropy analysis

No. of entry	Flow	Q_i^0 , kJ/t	$\Delta S_{irrev_i}^{out}$, kJ/(t·K)	%	ω_i^{tot} , %	B_i , kg/t	Rating
1	Excess water	178,451	58.68	7.7	4.89	1.66	V
2	Pulp	201,715	145.76	19.1	12.14	4.1	III
3	Secondary vapor of vacuum devices	211,255	127.76	16.72	10.64	3.62	IV
4	Molasses	4,393	1.41	0.2	0.12	0.04	IX
5	White sugar	12,476	3.98	0.52	0.33	0.11	VIII
6	Filtration sediment	21,000	7.89	1.03	0.66	0.22	VII
7	Water losses at saturation	27,964	10.82	1.42	0.9	0.31	VI
8	Heat «losses» in TTC	167,375	175.95	23.02	14.66	4.9	II
9	Electric energy «losses»	64,800	228.85	30	19.06	6.4	I
10	Total	889,430	764.2	100	63.5	21.36	

2. Reducing the final temperature of the water that leaves a factory. As the temperature of the water contained in the pulp is set by the technological mode of a diffusion installation and, accordingly, could not be reduced, it would only imply the in-depth temperature reduction of ammonia condensates. It should be noted that some ammonia condensate is used for technological purposes (the quenching of lime, filter flushing, sugar clarification, etc.). This requires maintaining a certain temperature, it is necessary to divide the condensate flows aimed at the in-depth cooling of their main part. It should also be noted that the in-depth cooling of the condensates requires the presence of appropriate products that they warm, possibly at low temperatures, and this is a technological task.

3. Using the heat of massecuite vapor. To implement this scenario, it is necessary to apply the measures related to decreasing the amount of massecuite vapor and increasing the level of recuperation of its heat:

3. 1. Send to boiling in vacuum devices products with an elevated density (dry matter content is to 70–72 % *DS*), which requires introducing vacuum machines with forced circulation and the system of their full automation.

3. 2. A part of the massecuite vapor is to be used at a factory to heat the diffusion juice (if necessary, simultaneously using it for heating barometric water). The greater effect is achieved when heating the diffusion juice after the reduced temperature diffusion machine, which is possible only by applying a diffusion-pressing juice extraction method.

4. Reduce energy losses into the environment. Introduce a set of measures to reduce heat «losses» into the environment, ensuring, first of all, the improvement of the insulation characteristics. In addition, ensure the utilization of heat from the emissions of saturation devices, as well as the stable continuous operation of a factory, high quality of the technological process, and the high quality of products at the factory.

5. Reduce electricity consumption. Given that much FER is used on electricity generation, it is advisable to implement a set of measures to reduce the costs of this item in the energy balance.

6. 2. Results of entropy analysis

The application of an entropy method makes it possible to expose the «internal» causes of energy imperfection of the thermodynamic system, which are inaccessible by means of classical analysis, and to suggest the appropriate compensatory measures.

For example, within the analyzed system, one could specify the following general sources of imperfection.

According to Fig. 2, which shows the result of the implementation of a principle of the «irreversibility energy compensation», we have a distribution of fuel, which is used to compensate for the set of the irreversibility of the combined system TPS+TTC. In our case, only 34 % of the total fuel is involved in the energy transformations of the TTC system. The remaining 66 % is lost at the stage of heat and electric energy generation in the amount that corresponds to the needs of TTC.

When compared, the energy balance method takes into consideration only 11 % of losses arising as a result of direct interaction of TPS with EE – the external irreversibility of TPS (Fig. 2). At the same time, the other 55 % are overlooked, caused by the internal irreversibility of processes in TPS, in other words, they are attributed to the balance of the TTC system. Thus, we have a situation when, even when maximizing the efficiency of energy transformations in TTC, the energy efficiency of the general system would increase partly.

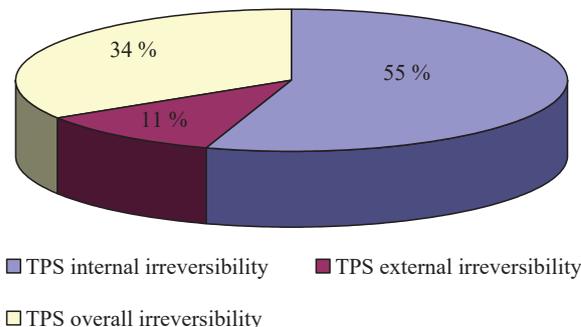


Fig. 2. The relative fuel consumption to compensate for the irreversibility of the processes in the systems «TPS» and «TTC»

According to the procedure of fuel distribution to compensate for the internal and external irreversibility of processes in the TTC system, the factors that impact the overall energy perfection of TTC could also be divided according to a given principle. The first ones imply a reduction in the irreversibility caused mainly by the irreversible heat exchange between subsystems with different temperatures and dissipative processes. To this end, the following measures could be applied: increasing the surface area of heat exchange, the use of heat exchanging surfaces with the intensification of heat exchange and with characteristics that ensure minimal hydraulic losses in the flow-through parts of the systems. It is important that the applied measures should lead to maximizing the entropy coefficient of the thermodynamic perfection [12] as a separate subsystem, as well as the system in general.

From the energy point of view, the reduction of internal irreversibility, whose manifestation is the increase in the potentials of heat carriers, creates conditions for a greater (deeper) use of secondary energy resources. It is worth noting that the increase in the perfection of the TTC internal structure leads also to a decrease in external irreversibility, which is, obviously, due to the reduction of energy at the boundary of cooperation between TTC and EE.

An additional reserve of fuel economy could be the use of residual potentials of the utilization of secondary energy resources. Analysis of the external «pyramid of imperfection» (Table 5) makes it possible to formulate the optimum sequence of activities and pre-estimate the positive effect. The specified factor can be implemented through two types of measures:

- 1) the application of additional systems with the possibility of using low-potential energy resources, as, for example, a pulp dryer driven by TPS flue gases;
- 2) the application of heat machines – thermo-compressors, heat pumps.

7. Conclusions

1. The thermodynamic analysis of the sugar production TTC as a single system has made it possible to link the fuel and energy resources supplied to an enterprise to the sources of their losses.

This has allowed us to justify the following basic energy efficiency measures:

- reduction of the amount of water entering a factory;
- reduction of the end temperature of the water that leaves a factory;

- using the heat of massecuite vapor;
- reduction of energy losses into the environment;
- reduction of electrical energy consumption.

2. Based on the results of entropy analysis and according to the principle of the «irreversibility energy compensation», it has been established that the fuel energy consumed by an enterprise is used to compensate for the internal and external

irreversibility of the processes. In particular, the dominant component in TTC is the external irreversibility, and in TPS – the internal irreversibility. It is important that only 34 % of the total fuel is involved in the energy transformations of the TTC system, whereas 66 % are lost at the stage of heat and electric energy generation in the amount that corresponds to the TTC needs.

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