Представлено дослідження інтеграції теплових потоків багатокорпусної випарної установки для концентрування сиропу сорго. Актуальність роботи визначається технологією процесу, який вимагає високих витрат енергії. Тому всі дослідження, спрямовані на зниження споживання зовнішньої енергії і підвищення ефективності роботи, актуальні і мають практичну цінність.

Головною метою роботи є створення науково обґрунтованого проекту з поліпшеними економічними показниками роботи, забезпечення економії споживання гарячого теплоносія (пари) і охолоджуючої води.

Рішення проблеми було проведено з використанням методу пинч-аналізу. Були ідентифіковані теплові потоки, що вимагають нагрівання та охолодження, і створений альтернативний проект, заснований на виборі значення мінімальної різниці температур ΔT_{min}. Це значення було розраховане і обґрунтовано на основі даних по тепловим потокам. У систему був доданий потік конденсату ретурної пари, надлишок тепла якого не використовувався досі. Для альтернативного проекту була запропонована схема розміщення теплообмінного обладнання, проведено розрахунок пластинчастих теплообмінників. Запроектована мережа теплообмінних апаратів дозволила знизити річні витрати пари на 18 %.

Аналіз економічної ефективності проводився порівнянням показників для двох проектів відділення попереднього нагріву сиропу для випарної станції. Запропонований альтернативний проект забезпечує економію споживаної потужності охолоджуючої води 35,9 кВт, пари, що гріє – 60,5 кВт. При процентній ставці податку 18 % реалізація альтернативного проекту окупиться через 4 місяці. В результаті чистий річний дохід підприємства планується більше на 16 %, при практично однаковому терміні окупності проектів. Застосування методів інтеграції теплових потоків дозволило розробити ефективний проект попереднього підігріву сиропу сорго перед випаровуванням та забезпечити економію зовнішніх утиліт

Ключові слова: рекуперація енергії, пінч-аналіз, випарна установка, пластинчасті теплообмінники, концентрування сиропу сорго

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THE INNVESTIGATION OF THE PROCESS STREAMS INTEGRATION IN THE MULTI-EFFECT EVAPORATION PLANT FOR THE CONCENTRATION OF SORGHUM SYRUP

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1. Introduction

Evaporation is currently the only actual industrial method of concentration of aqueous solutions, widely used in the chemical and food industries. Principles of construction of evaporating stations are common to all industries, concentrating liquid products, regenerating solvents or particular liquid crystal mixtures. Designing the technological processes of evaporation and the use of different types of equipment for evaporating stations are the focus of a large number of studies, among which we can highlight the practical applications in papers [1–3].

The relevance of the research in this direction is determined, first of all, by the technology of the process, which requires high energy costs. That is why the research, aimed at a decrease in consumption of external energy and an increase in efficiency of evaporating stations, is relevant and has practical value.

2. Literature review and problem statement

Evaporation in a multi-effect evaporator is typically the most energetically expensive process of obtaining a sugar

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solution. That is why the research, aimed at decreasing power consumption and increasing a recovery level are still relevant, both in terms of reducing the cost value of the product and in terms of decreasing emissions and of environmental security. Possibilities of optimal and rational design of multi-effect evaporators, the ways of energy saving have been carefully studied in regard to plants in the sugar producing industry [1–3]. Paper [1] presents the algorithm, based on the methods of process streams integration to optimize evaporator steams, widely used in the chemical and food industries. The main idea of the authors is that to develop new technological processes, implemented for evaporators, it is necessary to optimize the whole flow sheet, rather than separate parts of the system. However, it is not shown in the paper how and why the internal optimization of separate subsystems contradicts to the optimization of the system in general. Paper [2] addresses the integration processes of the evaporator station in the pulp and paper industry. The method for thermoeconomic analysis of the evaporator station, used to study the process of repeated evaporation of calcium bisulfite was proposed. Several variants of modeling the process for different values of minimum temperature difference were obtained. As a result, consumption of external energy can be reduced by 20 %, and in the case of the integration of the system of public services, their corresponding cost can be reduced by 23 % compared with the original scheme. It is not clear from the paper how it is supposed to integrate the system of municipal heat and hot water supply, having a pronounced seasonal and daily irregularity, into a new more efficient scheme of the evaporator operation. Paper [3] deals with the problem of using extra steam during sugar production as a source of heating sugar juice before evaporation and efficiency of their use in the thermal integration. This study presented the equation, which, according to the authors, can be used as a benchmark for thermal plants, including the integration of multi-effect evaporators. However, the presented analysis and the reference equation do not take into consideration the possibility of changes in the number of stages and the tendency of increasing the boiling point for stages with a simultaneous decrease in the time a solution stays in them.

Articles [4, 5] present the basic theoretical principles and practical guidance on application of the method of pinch-analysis. The methods of pinch-analysis make it possible to set the targets of design (optimal values of selected objective-functions, such as minimum values of the capacity of external utilities) before designing the network of recuperative heat exchangers and guarantee that these targets will be met during designing. The issues of thermal integration of multi-effect evaporators and cost-effectiveness of the obtained design solutions were considered.

To identify the ways of saving energy when operating the evaporating stations at sugar factories [6–8], researchers published the data on the overall analysis of the thermal scheme of the sugar factory in general. Thus, paper [6] presents the study of the heat integration of Savannah Sugar Company using the methods of pinch-analysis and software HENSAD. The obtained results showed significant saving of hot and cold utilities at minimal temperature difference of 7 °C.

In articles [7–9], examination of the sugar plant with the capacity of 3,000 tons of sugar beet processing per day was presented. The use of one of the methods of process streams integration (pinch-analysis) identified bottlenecks in the thermal plant network and its reconstruction project was developed. While implementing this project, specific consumption of thermal power can be reduced by 16 %. The payback period of the proposed modernization does not exceed the duration of the sugar beet processing campaign. The authors predict the possibility of further decrease in the power consumption at the rate of ~30 %.

Typical shortcomings of papers [6–8] may include the fact that the considered thermal scheme of the whole sugar factory does not take into consideration the reciprocal location of streams, that is, it is impossible to connect physically the streams, selected for heat integration, due to their location in different branches of production.

In the course of research, it was found that implementation of thermal integration of heat power for particular sections of a plant, specifically, those preparing or ensuring compliance with the technological process, is not less important in the general scheme. Examples of studying such enterprises, ensuring functioning of the main technological process are presented in articles [9, 10]. These papers deal with the issues of practical modernization of the system of sugar juice heating before evaporation. The operation of the system of heaters for the season of 2012–2013 was analyzed. Conducted monitoring of the operation of the installed heat exchangers proved that there is contamination of heat exchange surface and pressure losses in the first years of the operation of the system. Despite high efficiency of calculated and installed equipment, which was proved by the field observations, the authors could not establish the pattern of emergence and development of deposits on heat transfer surface, quality of sugar juice and temperature mode of the heaters' operation.

This enabled taking into consideration the specific features of sugar production with application of the principles of integration of thermal scheme of evaporation stations, considering the operation of auxiliary equipment, which was reflected, for example, in papers [11, 12]. Paper [11] contains the analysis of contemporary approaches to energy saving in the processes of the multi-effect evaporation. The extraction of data of the evaporator station of sugar syrup concentration (analysis of the technological scheme and identification of the process streams, requiring heating or cooling [4, 5]), was performed and weaknesses in organization of system's energy recovery were identified. Using the methods of heat integration, reconstruction of the existing technological scheme was performed: the network of exchangers, ensuring the maximum possible energy recovery in the system was planned and parameters of heat exchange equipment were calculated for economically reasonable value $\Delta T_{\min}$. It may be noted as shortcomings that process streams from other branches of production were not considered in these papers, and it was not shown how they affect the operation and thermal integration of the evaporation station.

In article [12], a universal technique for modeling food processes with the methods of pinch-analysis and the exergy analysis was proposed. The methodology was applied to the process of production of sugar from beets. Using software ProSimPlus®, the model of operation of the sugar factory with deviations within uncertainties of the industrial data on industrial enterprises of this type was constructed.

The considered studies on thermal integration of evaporating stations prove the fact that these objects are unique and need to be considered in each particular case. It is connected not only with the number of stages and the kind of the evaporated product, but also the operation modes (under pressure or vacuum). The main goal of any project is to minimize extraction of extra steam and maximum recovery of thermal energy. In fact, it is possible to say that the use of the classical schemes when designing such facilities does not provide sufficient heat recovery and cost savings. Designing evaporating stations with the preheating department requires a separate approach to calculation of thermal scheme and energy integration in each specific case. The need for research is related to the development of a new approach to designing the juice preheating department, based on maximum heat recovery to reduce operating costs.

3. The aim and objectives of the study

The aim of the present research is the search for an alternative solution in creation of a project of an evaporation station of sorghum syrup concentration, based on heat recovery, due to designing a new network of the heat exchange equipment. This will make it possible to improve the performance of the station by the criterion of minimization of hot and cold utilities consumption.

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

– construction and analysis of composite curves of technology streams;

– selection of economically reasonable $\Delta T_{\min}$, determining minimal required power of hot and cold utilities for an alternative project, location of heat exchange equipment;

– evaluation of forecasted economic efficiency of the alternative project.

4. Calculation scheme of the object and research procedure

It is necessary to design an evaporation station for concentration of sorghum syrup of initial concentration of DS=16 % to the concentration of DS=70 %. The original solution (sorghum syrup) has an initial temperature of 20 °C and mass flow rate of 2,000 kg/h. Saturated steam with the temperature of 140 °C is supposed to be used as the main hot utility. Thermophysical parameters and properties of sorghum syrup were accepted according to reference data and properties from paper [13].

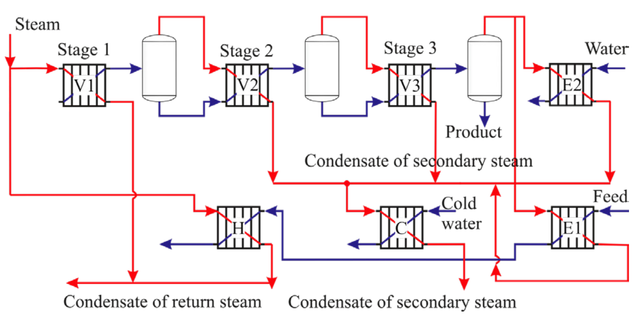

Fig. 1. General flow sheet of the proposed project of evaporation station for the concentration of sorghum syrup

The following flow sheet of evaporation was proposed – a three-stage evaporator under pressure with an equal amount of evaporated water for stages. The boilers of M10-MFG type, manufactured by company "Alfa Laval" (V1-V3, Fig. 1) were selected as evaporators. For preheating of syrup to the temperature equal to boiling point before feeding to stage 1 (evaporator 1), it is proposed to use a two-stage steam heating. Preheating of syrup up to the temperature of 80 °C is carried out by steam from the last evaporator (stage 3) and then up to 125.5 °C by return steam. Heat exchangers M6-MFG – E1 and H are selected for heating. Condensation of residual secondary steam from stage 3 was performed in the plate condenser M6-MFG (E2, Fig. 1), in this case, technical water was heated. Cooling of secondary steam condensate is produced in the heat exchanger M6-MFG (C, Fig. 1). All calculated heat exchangers are produced by company "Alfa Laval". The total mass flow rate of return steam with temperature of 140 °C by estimation will make up 692.6 kg/h.

Complete condensation of heating vapors was performed in all heat exchangers – evaporators and condensers. Secondary steam condensate enters the condensate line, is cooled, and collected in a storage container. Condensate of return steam returns to the boiler to generate steam. In this case, the used vapor-condensate system is open that is a condensate after the condensate remover enters the condensate collection tank. This tank is connected to the atmosphere and is not under excessive pressure, and the condensate is pumped into the boiler. In this case, the temperature of condensate in the tank does not exceed 100 °C.

To improve the performance of the technological scheme and to save steam and cooling water, we set the task to study the thermal scheme for possible improvement of energy recovery and reduction of energy consumption from external utilities. To accomplish this, pinch-analysis was selected [9, 11] as one of the most effective methods for studying thermal processes.

5. Analysis of data on heat streams, substantiation of selection of minimum temperature difference and design of a heat exchange network

To analyze the performance of the station operation and to determine the ways of creating an alternative project, the data examination and extraction was performed. In addition to the streams, considered in the original project, the stream of return steam condensate was taken into consideration. This stream is not involved in energy recovery but does not require the use of external utilities for cooling. The data on these streams are given in Table 1.

In the above Table, the following designations were accepted: T_s and T_t are the supply temperature and target temperature of a stream; g is the mass flow rate; CP is the heat capacity flow rate of the stream, determined as $c{\cdot}g$; where c, kJ/(kg·°C), is the specific heat capacity; $\Delta H = CP{\cdot}\left|T_s - T_t\right|$ is the required change in heat content of the stream (stream enthalpy [4, 5]), otherwise, heat load of the stream.

Total heat recovery, proposed for implementation in the original project, is equal to 962.5 kW. The composite curves of the streams of the system were constructed (without taking into consideration the stream of return steam condensate) and located on the temperature-enthalpy diagram so that the region of their overlapping by abscissa should be equal to heat recovery (Fig. 2).

This location of the components of the curve corresponds to the value $\Delta T_{\min}$=16.5°C, that is, the temperature difference in the heat exchangers, must not exceed this value, if they were placed in accordance with the rules of the pinch-analysis. However, it is not so, specifically, in the heat exchanger E1, minimum temperature difference of heat carriers is equal to 4 °C. To illustrate the shortcomings of the proposed project, its grid diagram is shown (Fig. 3), the analysis of which shows the heat transfer through the pinch, which leads to an increase in power of hot and cold utilities.

Table 1

Data on process streams of the evaporation plant

No	Name	Type	T_s, °C	T_t, °C	g, kg/s	CP, kW/°C	ΔH, kW
1	Secondary steam of evaporator 1	Hot	124.5	124.5	0.142	–	310,8
2	Secondary steam of evaporator 2	Hot	107	107	0.144	–	322.3
3	Secondary steam of evaporator 3	Hot	84	84	0.143	–	329.4
4	Condensate of return steam	Hot	140	100	0.145	0.617	24.7
5	Mixture of con-densates	Hot	105.1	30	0.429	1.803	135.5
6	Evaporation in evaporator 1	Cold	125.5	125.5	0.556	–	310.8
7	Evaporation in evaporator 2	Cold	108	108	0.413	–	310.8
8	Evaporation in evaporator 3	Cold	85	85	0.269	–	322.3
9	Original mixture (feed)	Cold	20	125.5	0.556	2.177	229.7
10	Technical water	Cold	25	55	1.587	6.626	198.8

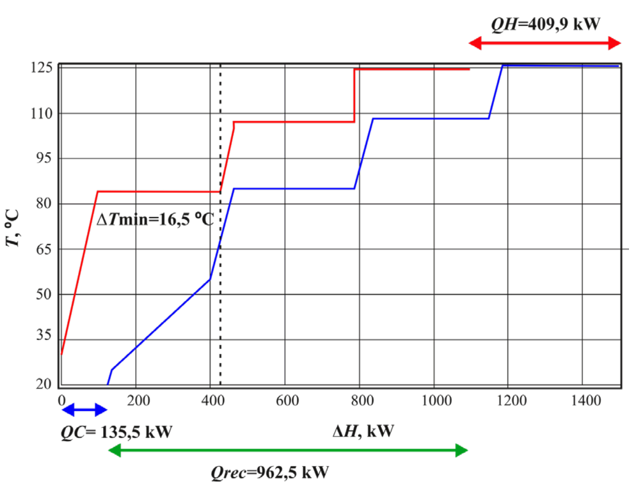

Fig. 2. Composite curves of the streams for the flow sheet in Fig. 1

To improve the existing project, the following actions can be proposed:

– selection of the value of $\Delta T_{\min}$ that is reasonable from the point of view of economy and specificity of production;

– addition to the system of considered streams, the stream of return steam condensation, the excessive heat of which has not been used so far;

– location of heat exchange equipment in accordance with the rules of the pinch- analysis to minimize consumption of external utilities;

– calculation and installation of new plate heat exchange devices.

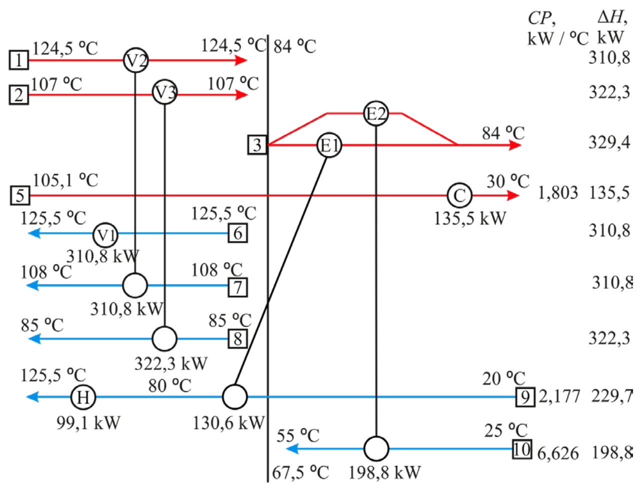

Fig. 3. Grid diagram for the flow sheet in Fig. 1

The calculations that predict the value of $\Delta T_{\min}$, which provides a minimum of annualized total cost of the project, were performed. Fig. 4 shows dependences of capital investments, cost of external utilities and the annualized total cost, obtained using the Hint Version 2.2 software. The optimal value of $\Delta T_{\min}$ is approximately equal to 4 °C.

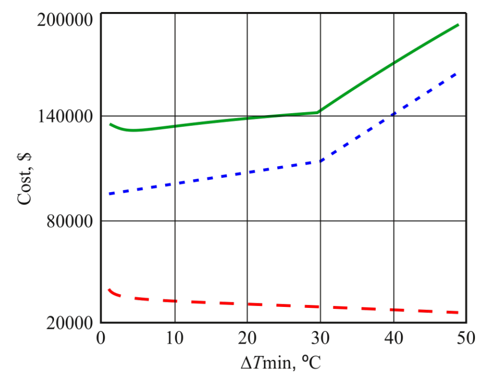

Fig. 4. Cost curves depending on $\Delta T_{\min}$. Dash line is capital investments, dot line is the cost of utilities, continuous line is the annualized total cost

To implement the project, we selected the value $\Delta T_{\min}$= =5 °C, which, on the one hand, is implemented in the plate heat exchangers, and on the other hand, does not lead to an increased heat transfer surface and, correspondingly, to a decrease in a linear velocity of heat carriers' motions in the channels. It is essential in this process, where one of the heat carriers is sorghum syrup, which by analogy with sugar syrup, tends to fairly intense contamination of the heat exchange surface at low velocities of heat carriers in the channels.

For the selected value $\Delta T_{\min}$=5 °C, composite curves were constructed (Fig. 5), already taking into consideration the stream of return steam condensate, the power of which can be used.

Pinch temperature of the hot streams is 84 °C, of the cold streams – 79 °C. The grid diagram after location of heat exchange devices takes the following form, Fig. 6.

For the project, the flow sheet of which is shown in Fig. 1, the heat transfer equipment, the cost specifications for which are given in Table 2, was proposed.

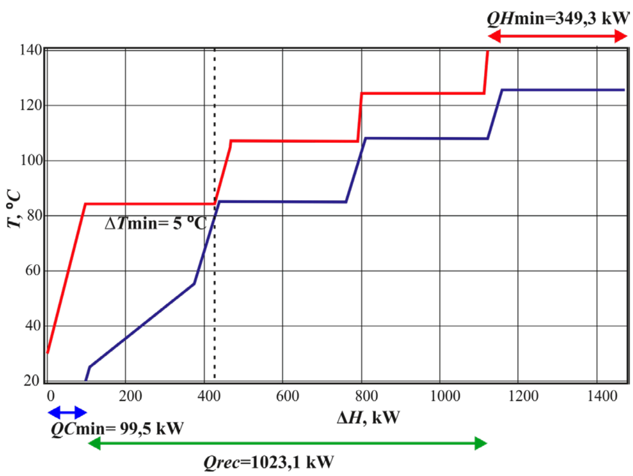

Fig. 5. Composite curves for streams in Table 1, constructed for value ΔT_{min}=5 °C

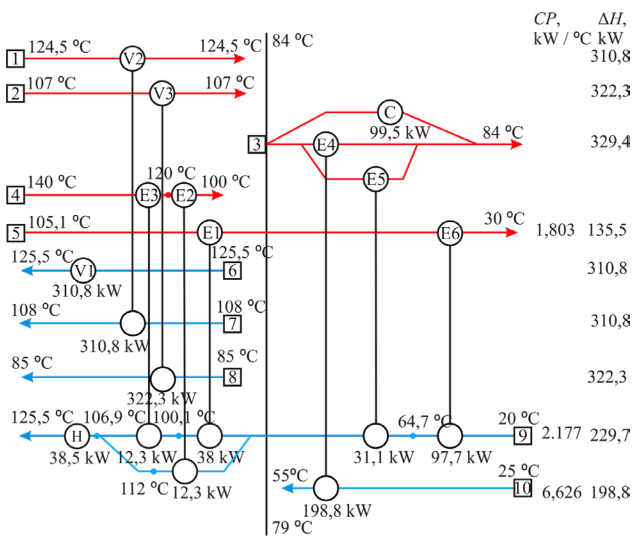

Fig. 6. Grid diagram with installed heat exchangers for value of ΔT_{min}=5 °C

Table 2

Type, number of plates and cost of heat exchangers, accepted for installation for the flow sheet in Fig. 1

Purpose	Type	Number of plates	Price with a 20 % VAT, USD
Heater *H*	M6-MFG	12	2,615.9
Cooler *C*	M6-MFG	12	2,615.9
Recuperative *E*1	M6-MFG	46	4,407.3
Recuperative *E*2	M6-MFG	22	3,144.3

For the alternate installation scheme for heat exchangers, presented in Fig. 7 and the corresponding grid diagram in Fig. 6, calculation of plate heat exchangers was conducted, the results of which are shown in Table 3. Calculation of the plate heat exchangers was performed using mathematical toolkit, developed with the use of the technique, presented in [14, 15]. Heat exchangers were selected form the nomenclature of gasketed heat exchangers, manufactured by company "Alfa Laval". Calculation of "liquid – liquid" devices was produced by the method of LMTD. Calculation of heat exchangers with phase transition in channels (condensation and evaporation) is based on step-by-step procedure of changing the mass flow rate of vapor content. To determine the pressure drop in the steam, the method of Lokkart–Martinelli for turbulent flow is used. When determining the cost of heat exchangers, we used the linear dependence of the form $C_{he}=C_{pl}\cdot n_{pl}+C_{frame}$, where C_{he} is the cost of the device, C_{pl} is the cost of one plate with gaskets, C_{frame} is the cost of frame, n_{pl} is the number of plates in the device. All calculated heat exchangers are single-pass, the plates are made of stainless steel AISI 316, gasket material is the rubber EPDM. The cost was determined according to the price-lists of company "Alfa Laval Potok", producing heat exchangers.

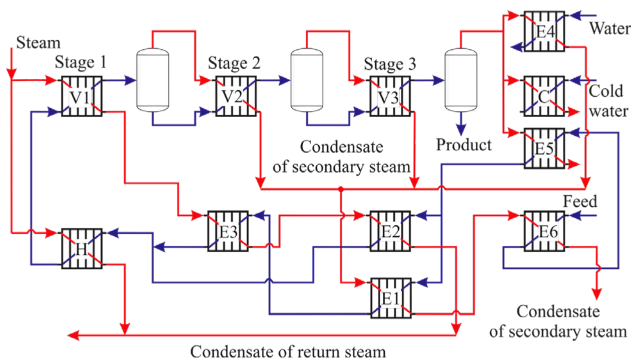

Fig. 7. Flow sheet of evaporation station for sorghum syrup concentration with preheating, designed based on pinch-analysis

Table 3

Type, number of plates and cost of heat exchangers, accepted for installation for the alternative design in Fig. 7

Purpose	Type	Number of plates	Price with a 20 % VAT, USD
Recuperative E1	M6-MFG	12	2,668.1
Recuperative E2	M3-FG	11	1,487.9
Recuperative E3	M3-FG	10	1,465.3
Recuperative E4	M6-MFG	22	3,144.3
Recuperative E5	M3-FG	40	2,181.9
Recuperative E6	M6-MFG	14	2,720.4
Cooler C	M6-MFG	12	2,615.9
Heater H	M6-MFG	10	2,511.0

As a result of analysis and design of two thermal schemata, two solutions that differ significantly in composition of the used equipment (plate heat exchangers) were obtained. This solution is characteristic when using the methods of pinch analysis [1–3]. Substantiation of the choice for implementation of a project is determined by cost-benefit analysis of equipment operation, which is presented below.

6. Discussion of results: cost-benefit analysis of the projects

For calculation of the economic indicators of the process, the following data were used: the price per 1,000 m^3 of gas is USD 422, *IRPT* (interest rate of profit tax) is 18 %, the number of working hours per year is 6,000. Based on these data, the calculated cost of steam was obtained –

USD 272.7 kWh/year, the cost of water is estimated as 10 % of the cost of steam.

Without energy recovery, the plant must consume the steam power of 739.3 kW, cooling water power of 464.9 kW. The scheme with heat recovery of the original project reduces the power of consumed steam up to 409.9 kW, of cooling water – up to 135.5 kW. The project using the principles of pinch-analysis gives a decrease in power of steam consumption up to 349.3 kW, of water – up to 99.5 kW. Thus, saving of steam power for the original and the alternative projects will amount to 329.4 kW and 389.9 kW, of water – 329.4 kW and 365.3 kW, respectively. The data on annual saving of steam and cooling water ΔS due to heat integration of the process streams and, consequently, a decrease in consumption of external energy sources are shown in Table 4.

Table 4

Indicators of annual saving of external utilities, capital and operating costs, annual net profit and payback period for flow sheets of evaporation station: 1 — Fig.1; 2 — Fig. 6

No.	ΔS, USD thousand	I, USD thousand	AOC, USD thousand	NAG, USD thousand	PP, years
1	98.8	21.3	5.1	76.8	0.27
2	116.2	31.3	7.5	89.1	0.35

Equipment costs included the cost of heat exchangers with VAT and installation cost (30 % of the cost of the heat exchangers). Design costs were determined in the amount of 15 % of the equipment cost. Design and equipment costs are capital expenditure (I) (Table 4). *AOC* (annual operating cost) included amortization (15 % of the capital costs of an enterprise) and maintenance costs (15 % of the equipment cost). *ANI* (annual net income) of an enterprise was calculated as $ANI=\Delta S-AOC$. *NAG* (net annual gain) of an enterprise was determined as $NAG=ANI\cdot(1-IRPT/100)$. *PP* (payback period) was calculated as $PP=I/NAG$. Comparative analysis of technical and economic indicators of the projects are shown in Table 4.

Thus, the use of a new alternative scheme, for which calculations were performed, makes it possible to significantly save costs of thermal energy. This was achieved through the installation of additional heat exchange equipment, enabling maximization of heat recovery in the juice preheating department.

The results of the conducted technical analysis of the projects show high efficiency and simplicity of the use of the proposed approach in evaluating the process of thermal integration of the systems of the interconnected heat exchange equipment. The main merit of the proposed approach is its consistent analysis when designing (from calculation of minimum temperature difference to economic efficiency assessment) combined with the use of different techniques (tools) for this evaluation. This approach uses high accuracy in calculation of each method, enables a wide variation in designed parameters, providing for direct and credible assessment of economic efficiency. Possible shortcomings are the requirements for high qualification in designing using the methods of heat integration and calculation of plate heat exchangers.

The presented research can be used when designing evaporation stations regardless of the type of feed for concentration, the number of evaporators and the quantity of steam to be remove. This approach is especially useful when designing new plants.

This study is a continuation of the studies on the development of methods for heat integration and their practical applications in various industries, including the food industry. Further direction of development is to create techniques, algorithms and mathematical toolset for automated assessment of the obtained alternative solutions between themselves and selection the optimal one by the specified criteria.

7. Conclusions

1. Based on a comprehensive analysis of the thermal scheme of the evaporation station, we compiled the table of the data of all thermal streams, which formed the basis for further research on their integration. To implement the syrup preheating, the composite curves of process streams were constructed, the pinch point and minimum temperature difference $\Delta T_{\min}$=5 °C was determined.

2. Based on the available data, the minimum required power of hot and cold utilities of the two projects was determined and the network of recuperative plate heat exchangers, ensuring maximum heat recovery, was designed. The proposed alternative project provides a decrease in consumed steam power up to 349.3 kW, of water – up to 99.5 to kW.

3. The presented cost-effectiveness analysis showed that the alternative project ensures saving in cold utility (cooling water) consumption of 35.9 kW, of hot utility (steam), of 60.5 kW in relation to the original project. At the interest rate of profit tax of 18 %, the project implementation will be pay off after about 4 months. When implementing an alternative project, due to increased heat recovery in the system, we achieve annual saving of steam and cooling water by 18 %. Net annual net gain of an enterprise is planned to increase by 16 % at a short payback period.

Acknowledgments

All design calculations of the plate two-phase evaporators and condensers, plate heat exchangers "liquid-liquid", as well as some techniques of process streams integration were made using software, developed by the company JSC "Sodruzhestvo-T" (Kharkov, Ukraine) and the Department of Integrated Technologies, Processes and Apparatuses of the National Technical University "KhPI".

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