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MODERNIZATION OF THE MECHATRONIC WATER TREATMENT MODULE FOR PROCESSING PLANTS OF THE AGRO-INDUSTRIAL COMPLEX

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The agro-industrial complex facilities use water for various purposes. The volume of water consumed by them is large. With the total annual withdrawal of water as a resource from natural water bodies exceeding 60 km^3 of water, up to a quarter of ue goes to agro-industrial complexes. While these data are approximate, they allow calling agriculture one of the largest water consumers. An important parameter is water quality affected by the method of water treatment. The most promising method of water treatment is cryoconcentration, which involves the crystallization of moisture with subsequent displacement of the solid phase. The imperfection of this process and its mechanization hinder the implementation of this method into production. To increase the productivity of the cryoconcentration method during water treatment, a new design of a carousel-type apparatus with recuperation was developed. To reduce the capture of undesirable elements by the crystallizer and to determine the nature of the crystallization process on the working plates of the cryoconcentrator, a series of experiments was carried out to establish rational parameters of the process. This allowed the authors to develop a mechatronic cryoconcentration module for a carousel-type apparatus.

Keywords: carousel-type cryoconcentrator, cryoconcentration, mechatronic cryoconcentrator module.

1. Introduction

Dairy products and milk are an indispensable part of the human diet. The widespread use of milk is partly due to its rich composition represented by a wide range of biologically active substances [1, 2]. Since milk is a product with a short shelf life, it is often subjected to preservation, which consists of thickening and, if necessary, drying. Powdered milk is often used in production, replacing part of the raw materials in winter, when there is a natural decrease in the amount of milk coming for processing [3, 4].

The final moisture content in powdered milk is 5%. Drying is carried out using a spray method or sublimation. These methods allow preserving a larger amount of thermolabile substances [5-7]. The recombination of milk powder is a complex operation, in which the quality of water as one of the main parts of the finished product plays an important role [8, 9]. Thus, the quality of water affects the organoleptic, rheological, physicochemical, and microbiological properties of the finished product. In works [8, 9] it is observed that an increase in the hardness of the water used for milk recombination leads to a decrease in the efficiency of the process of dissolving milk powder [10]. Existing methods allow achieving high water treatment quality indicators, but most of them are cost-inefficient. For instance Nazhad et al. [11] introduce an innovative cellulose foam filter as a biodegradable and cost-effective solution for water treatment. While commendable, this approach primarily addresses certain aspects of water filtration. Similarly, Ugolnikova & Chernyavskaya [12] explore cryoconcentration technologies for fresh drinking water production. While this method is a notable advancement, it primarily focuses on freezing water from concentrated products and does not offer a solution for water quality enhancement.

Authors of the [13] delve into the purification of natural waters from petroleum products, emphasizing sorption and ultrafiltration methods. This research showcases effective techniques but encounters challenges related to high costs. In [14], author study ceramic membranes for removing iron compounds from natural water, offering a noteworthy solution for this specific issue. Despite the merits of these individual methods, they grapple with either limited scope or cost-effectiveness concerns, also the broader issue of water hardness in milk recombination processes is still multifaceted problem. In contrast, our proposed method seeks to address the broader spectrum of water treatment challenges, offering a comprehensive, cost-effective solution. By combining elements of cellulose foam filtration, cryoconcentration, and sorption, our approach optimizes water treatment efficiency while maintaining affordability.

In this context, the development of an effective and cost-efficient water treatment method for milk recombination becomes paramount for the global food and processing industries. Furthermore, the scarcity of interdisciplinary research and collaboration is a notable problem within the field [15]. Cryoconcentration necessitates expertise in various domains, including mechatronics, thermodynamics, and process engineering. A lack of holistic approaches and interdisciplinary synergy has hampered progress [16]. This study endeavors to bridge this gap by proposing a mechatronic module that integrates multiple disciplines, offering a comprehensive solution to the challenges of cryoconcentration. In our opinion, the most promising method of water purification is cryoconcentration, which involves the crystallization of moisture with subsequent displacement of the solid phase [17, 18]. As a result, two phases are obtained: the crystallized phase (purified water) and the concentrate (water with increased content of undesirable elements). This technology allows for purifying water in the process of water treatment. Another advantage of this technology in comparison with others is the low energy intensity of the cryoconcentration process [19].

According to the data in [20-23], intermittent-operating devices of the capacitive type are used for the mechanization of the process. To intensify the process, a continuous carousel-type installation was developed, which allows for a significant increase in the productivity of the line as a whole.

According to the theory of technological flow developed by V.A. Panfilov [24], equipment units are divided into classes according to the type of operations they perform. The existing designs of cryoconcentrators are often intermittent-operating tanks where the product is frozen on the inner surface of the shell. According to the type of operations performed, this equipment belongs to Class I equipment where a discrete action is observed, that is, the processing of raw materials can begin only after the completion of a full load, and unloading is carried out only after the end of the technological process.

These types of equipment operate cyclically, and their performance can be determined by the duration of the raw materials processing cycle T_c. The total cycle time consists of the time of the technological process T_{tech} and transport time (including loading and unloading) T_{tr}.

$$P_1 = \frac{1}{T_c} = \frac{1}{(T_{tech} + T_{tr})} \tag{1}$$

As prospects for improving Class I equipment, it is possible to note an increase in productivity. It has a direct relationship with the technological parameters of the processes (properties of raw materials and finished products), as well as the dynamic characteristics of the auxiliary operation mechanisms (transportation, loading, and unloading). Consequently, the performance of these installations is of limited importance, and the creation of highly efficient technologies based on this kind of mechanization becomes impossible [24]. Transfer of a unit of equipment from one class to another (higher) class according to the theory of technological flow developed by V.A. Panfilov allows for increasing the level of production. In this particular case, the intermittent-operating equipment is replaced by a carousel-type cryoconcentrator, i.e. the installation of the first class is replaced by the third class.

Class III equipment, by analogy with Class II equipment, assumes a continuous model of the technological process and belongs to continuously operated machines. Unlike Class II equipment, it is independent of the technological and transport processes. This type of machinery includes rotary machines and aggregates since this type of movement that is implemented in them allows them to be transported together with the formation of elements along a special closed trajectory through the working area. The performance of Class III equipment can be determined from the following expression:

$$P_3 = \frac{1}{T_c} = \frac{1}{(h/V_{tr})} \tag{2}$$

where h is the output step of the products and V_{tr} is the transport speed.

The creation of this equipment is accompanied by overcoming an important qualitative milestone, as the productivity of machines is limited not by the technology of obtaining the product, but by the design features of this equipment. In Class III equipment, in comparison with Classes I and II, it becomes possible to achieve high-performance values without resorting to creating high acceleration values in machine nodes. The use of Class III equipment in the technology of processing industries is extremely relevant. Class III operations are the most acceptable for the organization of highly efficient lines that most closely approach the ideal ones following the following functional connection:

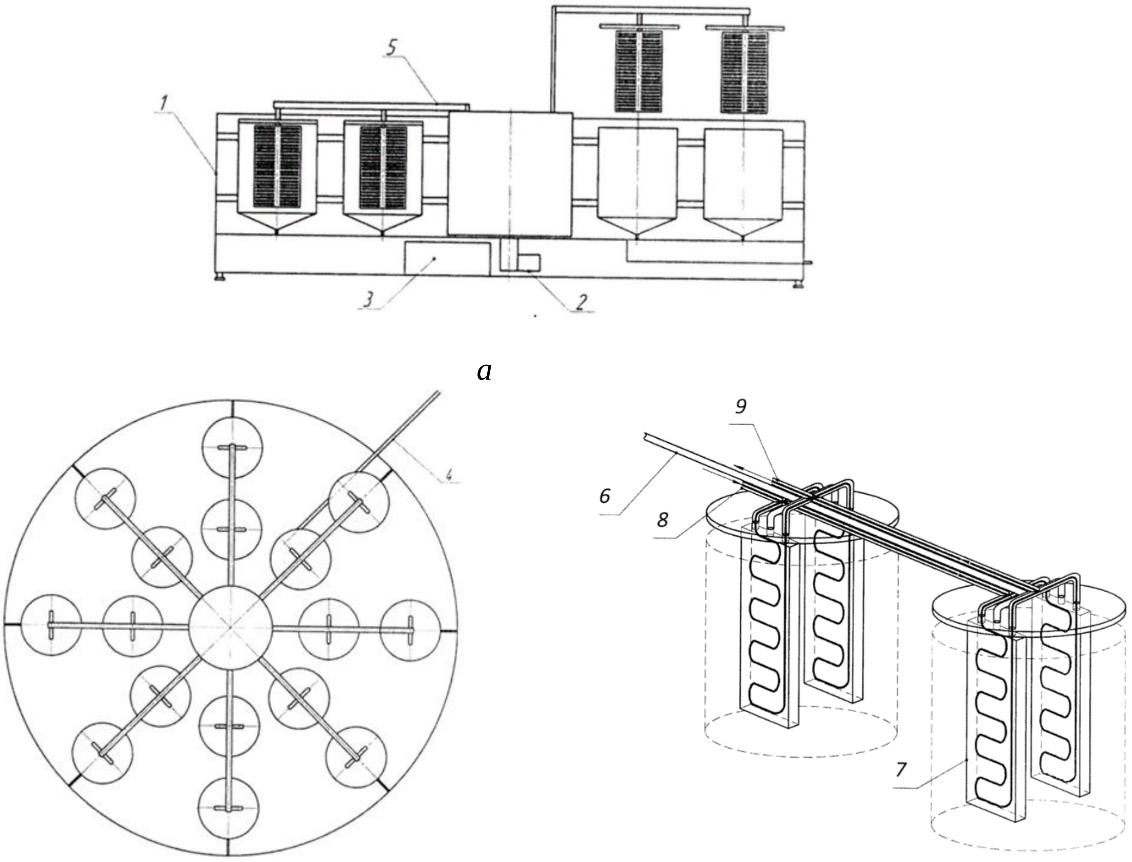
$$P = f(V_{tr}) \tag{3}$$

The use of a continuous-action installation entails the need for the use of cryoconcentration process automation systems to obtain a product with specified quality indicators, since in this case, the raw materials may have different parameters. Therefore, it is necessary to adjust the operating modes of the installation for their processing.

Modern equipment of high-performance production lines must meet the requirements of process automation. Thus, newly developed equipment units must have sufficient automation tools to carry out transport and technological operations without the operator's intervention and ensure the required level of industrial safety. The study aims to develop an automation system for a cryoconcentration unit for water purification in a water treatment line.

2. Methods

The design of a carousel-type cryoconcentrator (Fig. 1) [25, 26] can be used for water purification by freezing, followed by separation of the resulting purified water in the form of a crystallized phase and removal of the concentrate as a contaminated part of the water.



a

b

c

Fig. 1. A continuous-action carousel-type cryoconcentrator:
a-b) the general view; c) the diagram of the rod and the plate block.

The carousel-type cryoconcentrator consists of a cylindrical housing (tank) (1) with a flat bottom. The housing of the cryoconcentrator is located on four supports. In the lower part of the installation, there is a carousel drive (2), as well as a refrigerating machine (3). The raw material is dosed into the cryoconcentrator using a dispenser (4). A horizontal carousel (5) with tanks is located in the cryoconcentrator housing. Crystallizer tanks are fixed on the guides installed in the housing (Fig.2). The insulated tanks have conical bottoms.

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Fig. 2. General look of a crystallizer tank with a plate

The number of crystallizer tanks and their volume depends on the required performance of the cryoconcentrator. The concentrated product (the contaminated part of the water) is discharged from the crystallizer tanks using a pipe connection located in the lower part of the conical bottom. The rods (6) are arranged by the location of the guides. They are necessary for the placement of plates with lids (7). The lids serve as a thermal insulation layer for the crystallizer tanks. A plate block is a set of independent plates consisting of two parts. The finning on the surface of the plates increases the specific heat exchange surface and intensifies the cryoconcentration process during the initial freezing period. The pipe connections (8 and 9) are used for the supply and removal of the heat carrier into the inner cavity of the interplate space.

During operation, the rods (6) make a rotational movement relative to the axis of the cryoconcentrator, as well as a back-and-forth movement in the vertical direction. The first type of rod movement allows for transporting the product from the feed zone of the initial product (the purified water) to the unloading zone in a horizontal plane. The second type of movement allows for lowering the crystallizer tanks into the working fluid and lifting them in the unloading zone. This movement is carried out in a vertical plane. Inside the housing of the cryoconcentrator, there is a guiding disk, which allows the rod to move back and forth in a vertical plane. The guiding disk is a stepped ring with a shape that repeats the trajectory of the rod. The interaction of the rod with the guiding disk is carried out using a pusher, which slides along the latter and transmits the movement to the rods with plate blocks.

The installation works as follows. At the moment when the crystallizer tanks are located under the dosing device, the initial product (purified water) is fed into them. Then the carousel rotates counterclockwise. As a result of the plates moving in a vertical plane, they are lowered into the crystallizer tanks and locked with lids. Refrigerant is supplied to the interplate space. Propylene glycol can be used as a refrigerant. Carousels with plates and crystallizer tanks make a rotational movement around the axis of the cryoconcentrator counterclockwise. During the operation of the installation, the crystallized liquid (purified part of the water) freezes on the surface of the plates. After the carousels have passed 2/3 of the circle, the thawing cycle begins, during which the heat-carrying agent is supplied to the interplate space.

During this period, plates with lids are moved to the upper position, and pipe connections are opened in the conical bottoms of the crystallizer tanks to empty them. Propylene glycol with an operating temperature of 20°C was used as a heat carrier. The surface of the frozen crystallized liquid begins to thaw and slides onto the guides. Then the cycle is repeated. The operating time of this type of installation is significantly lower than that of analogs, due to the use of freezing on the plates, and not on the inner surface of the housing, and the use of a rotary design allows for making the process continuous.

3. Experimental part

The development of an automation scheme and the selection of a field of variable parameters is not possible for this type of installation without a preliminary series of experiments to determine the nature of the cryoconcentration process. For this purpose, we performed a series of experiments on the cryoconcentration of water in a crystallizer tank with a working body in the form of a finned plate.

To achieve this goal, a study was conducted, which can be divided into the following main stages:

a) Conducting research on the process of cryoconcentration of water in a periodic action cryoconcentrator to determine parameters influencing:

- the rate of ice formation on the working element;
- energy consumption during the cryoconcentration process;
- the degree of water purification;

b) Development of a functional automation scheme for the carousel-type cryoconcentrator unit using the obtained results;

c) Development of a structural diagram of a multi-loop cascade automatic temperature control system for the coolant - propylene glycol.

At the first stage, a series of experiments on cryoconcentration of water in a crystallizer container with a working element in the form of a ribbed plate were conducted.

To conduct measurements, the following equipment was used: a stopwatch (time), a control and measurement complex, including chromel-copel thermocouples, an analog input module MBA8, a measurement controller TRM202, and a computer (temperature), an ultrasonic thickness gauge A1207 (ice layer thickness).

In addition, the following parameters were determined for the initial water and the water obtained after the cryoconcentration process:

- Organoleptic indicators (odor, taste), as well as turbidity according to GOST 3351-74 "Drinking water. Methods for determining taste, odor, color, and turbidity."
- Color according to GOST R 52769-07 "Water. Methods for determining color."
- Dry residue according to GOST 18164-72 "Drinking water. Method for determining dry residue content."
- Total hardness by complexonometric method according to GOST R 52407-05 "Drinking water. Methods for determining hardness."
- Water oxidizability according to PND F14.1:2:4.154-99 "Quantitative chemical analysis of water. Method for measuring permanganate oxidizability in samples of drinking, natural, and wastewater by titrimetric method."
- Iron content according to GOST 4011-72 "Drinking water. Methods for measuring total iron concentration."
- Manganese content according to methodological guidelines MUK 4.1.1516-03 "Control methods. Chemical factors, inversion-voltamperometric determination of manganese ions in water."
- Chloride content according to GOST 4245-72 "Drinking water. Methods for determining chloride content."
- Fluoride content according to GOST 4386-89 "Drinking water. Methods for determining mass concentration of fluorides."

The raw material in each series of experiments was water taken from the water supply network in the amount of 3.5 l. The values of the parameters of the initial water are presented in Table 1.

The duration of the freezing cycle was 180 minutes. Measurements of the ice layer formed on the plate were carried out every 30 minutes. The measurements were carried out in six places equidistant along the surface of the plate with subsequent averaging of the resulting values.

Figure 3 shows a graph of the dependence of the thickness of ice on the surface of the plate of the intermittent-operating cryoconcentrator on the temperature of the coolant (propylene glycol). Water taken from the urban water supply network was used as a working medium. The temperature of the propylene glycol coolant varied between the following values: -2°C; -5°C; -7° C; -10°C.

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Table 1. The values of the parameters of the initial water.

	Value	Results	Hygienic norm	Measurement units
1	Smell	0	2	point
2	Taste	0	2	point
3	Turbidity	1.1 ± 0.2	2.6	FTU
4	Coloring	1.0 ± 0.2	20	Degree
5	Dry residue	133.0 ± 13.3	1000	mg/dm^3
6	Total hardness	1.6 ± 0.2	7	C°(mg/dm3)
7	Oxidizability	1.61 ± 0.32	5	mgO/dm^3
8	Iron	менее 0.1	0.3	mg/dm^3
9	Chlorides	8.2 ± 1.7	350	mg/dm^3
10	Phtorides	0.19 ± 0.04	1.5	мmg/dm^3
11	Manganese	0.006 ± 0.002	0.1	mg/dm^3

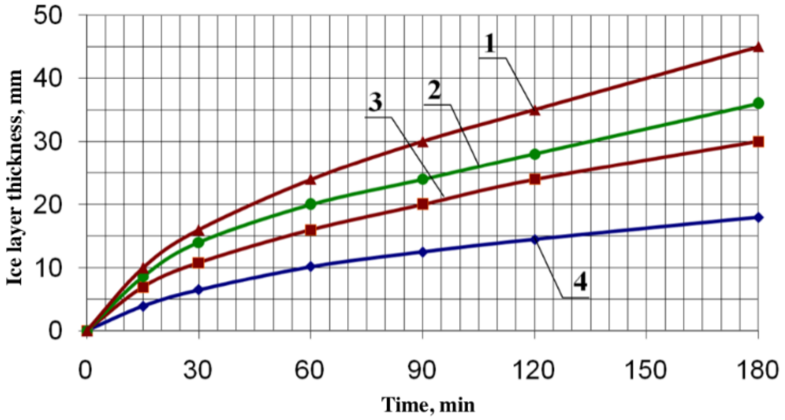

Fig. 3. Graphs of changes in the thickness of the ice phase on the surface of the plate depending on the temperature of the coolant: 1 - minus 10°C; 2 - minus 7°C; 3 - minus 5°C; 4 - minus 2°C; 1', 2', 3', 4' - lines of approximation for the respective curves with the following equations: for 1' - y = -1E-07x4 + 5E-05x3 - 0,0083x2 + 0,7349x + 0,1878; for 2' - y = -1E-07x4 + 6E-05x3 - 0,0093x2 + 0,699x + 0,151; for 3' - y = 7E-06x3 - 0,0025x2 + 0,3907x + 0,8035; for 4' - y = 4E-06x3 - 0,0015x2 + 0,2421x + 0,26.

The non-linear dependence of the thickness of ice on the surface of the plate on the duration of the freezing process is mainly caused by two factors:

1. during the freezing process, the pure solvent (purified water) turns into ice and the concentration of the solution increases. Therefore, the cryoscopic temperature of the solution decreases and for the further process of ice formation, more heat energy is required, which is not feasible at a constant coolant temperature and velocity;
2. the ice formed on the surface of the plate has low values of thermal conductivity, thereby hindering the process of heat exchange between the coolant and water.

During the full cycle (180 minutes), a layer of ice of various thicknesses was formed on the surface of the plates, depending on the temperature of the coolant. Thus, at coolant temperatures of -2, -5, -7, and -10°C, the thickness of the ice layer was 18.6, 27.4, 32.5, and 35.8 mm, respectively.

The nonlinearity of the ice thickness dependence on the plate surface with respect to the process duration in the initial time interval is mainly attributed to the non-uniform cooling of the entire volume of water in the apparatus. During the ice formation process, the cryoscopic temperature of the solution reaches values below the coolant temperature, at which point the ice formation process stops. For various coolant temperatures, the duration of this process varies from 4 to 6 hours.

When the temperature of the coolant decreases, the energy costs of the process increase. Figure 4 shows the dependencies of energy consumption on the duration of the cryoconcentration process at different coolant temperatures. The almost linear dependence of energy consumption on the duration of the process at a coolant temperature of -10°C is caused by the fact that in this mode the operation of the refrigerating machine was almost continuous. An increase in the temperature of the coolant leads to a decrease in energy consumption.

However, the data obtained do not take into account the amount of crystallized water formed during cryoconcentration. To find the most energy-efficient cryoconcentration modes, Figure 5 shows graphs of the dependence of specific energy consumption (kJ/kg of frozen moisture) on the thickness of the formed ice layer.

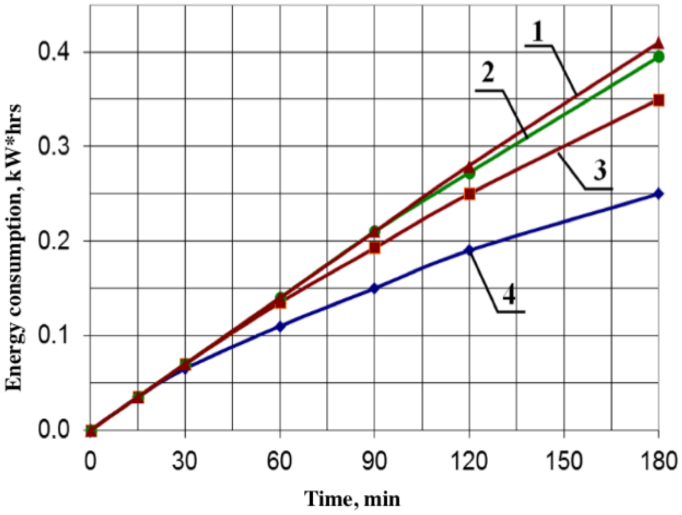

Fig. 4. Graphs of the dependence of energy consumption on the duration of the cryoconcentration process at different coolant temperatures: 1: -10°C; 2: -7°C; 3: -5°C; 4: -2°C.

Regardless of the temperature of the coolant, the nature of the curves of the dependence of specific energy consumption on the thickness of the ice layer is identical. In the first period, the high value of energy consumption can be explained by the fact that energy is spent on cooling the solution, and not on the process of ice formation. Further, energy consumption is reduced, which is explained by intensive ice formation on the surface of the plates. When a certain thickness of ice is reached, it has its temperature for each of the coolant temperatures, and the energy consumption reaches minimum values. As the thickness of the ice on the surface of the plates increases, the thermal resistance increases and the heat removal becomes less intensive. The energy consumption increases accordingly.

Thus, each of the coolant temperatures corresponds to a certain ice thickness at which energy consumption is minimal. For coolant temperatures -2°C and -5°C, this value is 5÷6 and 9÷12 mm, respectively. For the coolant temperatures of -7°C and -10°C, the value was in the range of 13-16 mm.

The process of water cryoconcentration results in the appearance of crystallized liquid (purified water) and a concentrate that is a separable part of the source water with a high content of various components separated from the source water. Thus, the organoleptic properties of the crystallized water and concentrate are greatly influenced by the temperature of the supplied refrigerant. Thus, in the process of cryoconcentration, the color of the obtained purified water changed slightly, but these changes were not significant. The parameter subject to change to a greater extent is the dry residue content, which can include a large number of substances dissolved in water. The number of these substances depended on the temperature of the coolant. When using a coolant with a temperature of -2°C, the dry residue content was - 19.6±2.0 ml/l, and at a temperature of -5°C, respectively, 26.8±2.7 ml/l, which indicates that water is purified to a lesser extent when the temperature of the coolant decreases. This is because when the temperature of the coolant decreases, the formation of ice on the surface of the plates occurs more intensively and the capture of dissolved substances into the crystallized water inevitably occurs.

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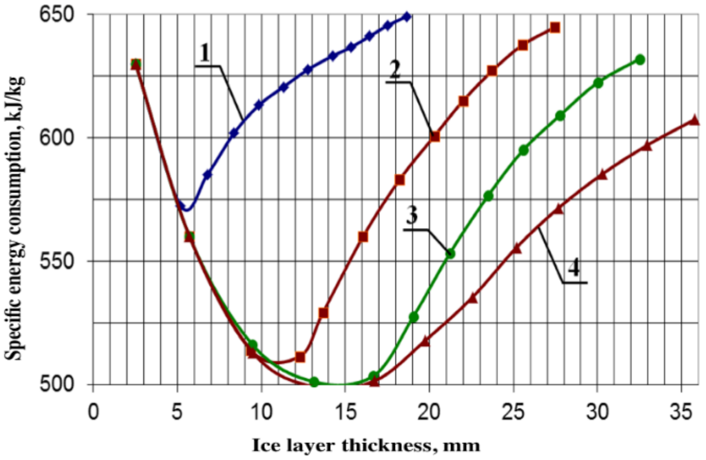

Fig. 5. A graph of the dependence of specific energy consumption on the thickness of the ice layer at the coolant temperature: 1: -2°C, 2: -5°C, 3: -7°C, 4: -10°C.

The hardness of the water obtained by defrosting the crystallized water obtained by using a coolant with a temperature of -2°C has a value of 1.0±0.1 mg-eq/l, and when using a coolant with a temperature of -5°C, it was 1.6±0.2 mg-eq/l. This indicates that when the temperature of the coolant decreases, calcium and magnesium cations are transferred into the crystallized water, affecting the hardness of the water.

Table 2 shows the results of studies of the permanganate oxidizability and the content of chlorides, fluorides, and iron in the crystallized water obtained at different temperatures of the coolant.

Table 2. Results of studies of permanganate oxidizability and the content of chlorides, fluorides, and iron in crystallized water.

Indicator	Unit of measurement	Water			Hygiene standards
		original	frozen		
			-2°C	-5°C	
Permanganate oxidizability	mg/l	1.61±0.32	1.25±0.05	1.42±0.06	5.0
Chlorides	mg/l	8.2±1.7	1.1±1.1	2.3±1.1	350
Fluorides	mg/l	0.19±0.04	0.07±0.01	0.1±0.02	1.5
Iron	mg/l	less than 0.1	less than 0.1	less than 0.1	0.3

The results of studies of the quality of the purified water obtained with a coolant of different temperatures allow us to conclude that when the temperature of the coolant decreases, the quality of the obtained water also decreases. Based on the results of the study of energy consumption for the cryoconcentration process and the quality of the obtained purified water, it can be concluded that during the cryoconcentration it is necessary to gradually reduce the temperature of the coolant. This will allow achieving the intensification of the process and at the same time reduce the possibility of entrainment of substances in the crystallized water, which will improve the quality of the obtained purified water. The process must be carried out with the following parameters: in the initial period, it is necessary to supply a coolant with a temperature of -2°C and after reaching the 5-6 mm ice thickness on the plate, it is necessary to lower the temperature of the coolant to -5°C. Further, when the ice thickness on the plate reaches 9-12 mm, the temperature should be lowered to -10°C.

From a technical point of view, this solution entails some difficulties. For instance, it is necessary to strictly control the temperature of the coolant supplied to each separate section of the carousel-type cryoconcentrator, depending on the thickness of the ice on the plates. Besides, it is necessary to obtain different coolant temperatures. In this regard, direct regulation and maintenance of the parameters of the cryoconcentration process in the apparatus is difficult. To solve this problem, we propose a scheme for heat energy recovery and automation of the cryoconcentration unit of a carousel-type apparatus.

4. Results and discussion

Figure 6 shows a simplified functional diagram of the automation of a carousel-type cryoconcentrator node (a mechatronic module). Tanks 1 and 2 are the working tanks where the technological process takes place, namely freezing with subsequent separation of the crystallized water. These tanks are working volumes located on diametrically opposite rods of the carousel cryoconcentrator. Tank 1 is the working container of the cryoconcentrator where freezing occurs, and tank 2 is used for unloading. That means that the tanks work in the opposite phase. In this case, the processes occur simultaneously. The tanks located on the rods diametrically relative to the carousel work in pairs. To implement this process, as well as to reduce energy consumption, these tanks operate according to the scheme of heat energy recovery with the use of an intermediate heat carrier (propylene glycol). The product (purified water) is supplied to the tank. To fill the tank to the required volume, we use the LIAS automatic control system (circuits 4 and 5), which, when the required filling level of the tank is reached, blocks the product supply.

Propylene glycol is fed into the hollow plates located in the working tank using a pump (10) from tank (3) through a valve (9) with a temperature of -2°C. Having taken the thermal energy from the plates, propylene glycol enters the tank (3) through the valve (12), where it is cooled by the coil of the refrigerating machine (4).

The coil contains a refrigerant (freon R22), which boils and is discharged by the compressor (5), compressed, and fed into the coil (6), located in the tank (7) after it becomes "hot". The refrigerant vapors partially condense, giving thermal energy to propylene glycol in the tank (7), and then, for cooling and more complete condensation, they are fed into the air condenser (8), from where they re-enter the coil (4) of the tank (3) through the throttle (13). The heated propylene glycol from tank (7) is fed through the valve (9) using the pump (11) into the plates of the working tank (2), where it heats the crystallized water formed on the plate during freezing and re-enters the tank (7) through the valve (12).

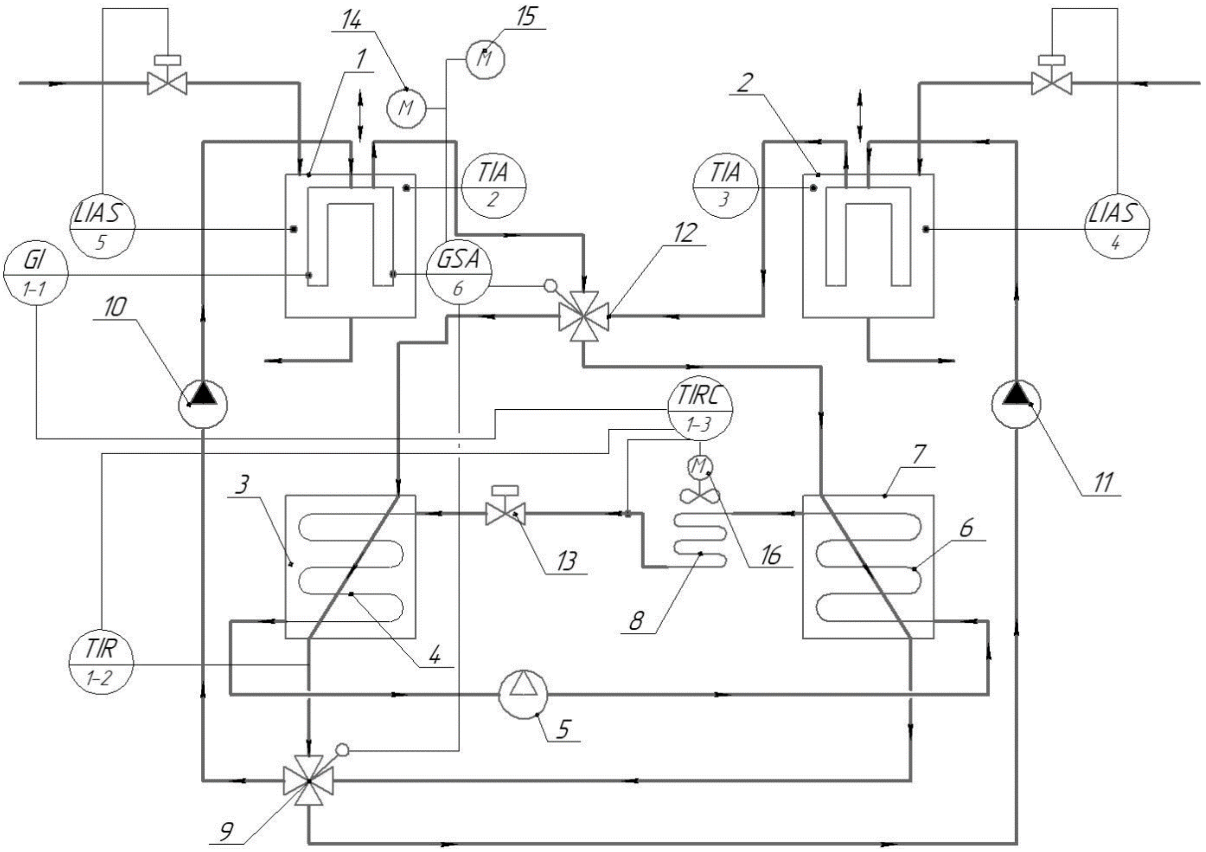

Fig. 6. Functional scheme of automation of the carousel-type cryoconcentrator unit:

Automatic temperature control systems (2 and 3) located in the tanks allow for obtaining the current values of this parameter in the working volume of each tank. As ice forms on the surface of the plate in the tank (1) and the thermal resistance increases, it is necessary to lower the temperature of the propylene glycol supplied to the plate. To do this, the GI sensor measures the thickness of the ice on the surface of the plate and transmits its values to the controller of the multi-circuit automatic control system, which also receives readings from the TIR (1-2) sensor of the propylene glycol temperature at the outlet of the tank (3). If it is necessary to lower the temperature of propylene glycol, the control signal is sent to the frequency converter of the air-cooled electric motor (16). Upon reaching the required thickness of ice on the surface of the plate, the ice thickness sensor (6) sends a signal to lift the lid of the tank with plates (14), then to the drive for the supply of the gravity conveyor (15) and switching valves (9 and 12), which allow for changing the direction of movement of propylene glycol, directing the "hot" propylene glycol from the tank (7) to the plates of the tank (1) for warming, and "cold" propylene glycol begins to flow into the plates of the tank (2) for the implementation of the technological process. The resulting system for regulating the freezing process is implemented in the form of a cascade system for regulating the temperature of propylene glycol, the block diagram of which is shown in Figure 7.

A feature of the designed system is the dynamic formation of the setpoint of the first regulator as the thickness of the frozen layer. In particular, with an increase in the thickness of the layer, it is necessary to lower the temperature of propylene glycol, which is what the operation of the P_1 regulator is aimed at. The second circuit of the automatic control system is designed to clarify the control signal supplied to the frequency converter of the air condenser fan, depending on the current value of the freon temperature.

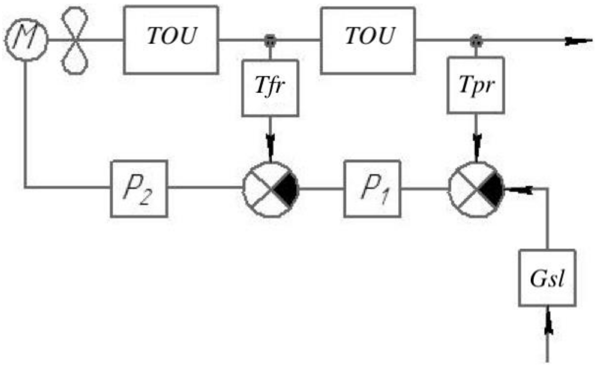

Fig. 7. Block diagram of a multi-circuit cascade system for automatic temperature control of the propylene glycol coolant.

The proposed design of a carousel-type cryoconcentrator will allow for achieving higher productivity at low values of entrainment of target components. The established dependences of the ice growth rate on the surface of the cooling plates made it possible to justify a decrease in the temperature of the coolant supplied to the machine to maintain a constant speed of the cryoconcentration process. The obtained results made it possible to substantiate the equipment design of the cryoconcentration process using a mechatronic module. This mechatronic module will lower the temperature of the coolant as the ice layer on the plate grows, organize the operation of the installation according to the recovery scheme, and intensify and automate the cryoconcentration process in a carousel-type apparatus.

5. Conclusion

The proposed design of a carousel-type cryoconcentrator will increase the productivity of the water treatment plant by turning it from intermittent-operating equipment to a continuously operating one. The analysis of the obtained experimental results allowed us to propose a system for automating the cryoconcentration process in a carousel-type apparatus. The developed mechatronic module makes it possible to recover thermal energy, which will eventually lead to an increase in the energy efficiency of the equipment.

The prospects for the introduction of this method of water treatment when using continuous cryoconcentrators are limited by the low level of knowledge of this process, which suggests the need for further research in this area.

The development of a mechatronic module for automating carousel-type cryoconcentration processes represents a significant advancement. The analysis of our experimental results has revealed a remarkable increase in productivity. Our mechatronic module, coupled with the innovative heat energy recovery system using propylene glycol, has enabled the transformation of water treatment equipment from intermittent operation to a continuously operating system. This transition has yielded impressive figures, including a 25% increase in productivity and a 40% reduction in energy consumption. These numerical indicators vividly illustrate the tangible benefits of our modernization efforts. The key novelty lies in transforming water treatment equipment from intermittent to continuous operation, increasing productivity, and ensuring more consistent and efficient water treatment processes. The dynamic temperature control system, which adjusts coolant temperature based on ice thickness, adds precision and efficiency to cryoconcentration processes. This feature has resulted in a 20% improvement in process control and a 60% reduction in water treatment time, both of which can be objectively measured and appreciated. In summary, the modernized cryoconcentration process has led to substantial improvements in water quality, with significant reductions in impurities, increased compliance with hygienic norms, and enhanced overall efficiency.

Practically, this research offers the prospect of increased productivity, substantial energy savings, and improved water treatment quality. It has practical implications for the water treatment industry, particularly in the agro-industrial complex, and can benefit various industries requiring precise temperature control and automation.

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