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DEFINING WAYS FOR IMPROVING AUTOMATIC TECHNOLOGICAL LINES FOR SHOCK FREEZING OF FOOD PRODUCTS

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This study redesigns technological lines for dynamic shock freezing of food products with a long shelf life. The task is to reduce energy consumption per product unit and decrease the cost of maintaining technological lines.

It was established that replacing analog sensors of technological process parameters with digital devices makes it possible to shorten transition intervals between different operating modes of the line by more than 10 minutes. Applying controlled valves and gates in the equipment makes it possible to optimize automatic freezing modes, taking into account both the quality indicators of frozen products and the efficiency of equipment operation.

Modernization of equipment makes it possible to devise more effective automatic operation programs for shock freezing technological lines under the supervision of a single operator. This approach involves the selection of different automatic technological freezing modes for different products. In this case, product parameters (thermal conductivity, percentage of water content, dimensions of individual products) and the final state of frozen products (deep freezing to –30°C, quick freezing to –10°C, or others) are taken into account.

The service functions of the automatic control system in the technological line have been expanded. In particular, these include self-diagnosis, rapid automatic response to emergencies, automatic warning about refrigerant leakage, enhanced informativeness of the text-symbol display, as well as convenience of the operator-equipment interface. Experimental studies on the modernized automatic line have shown a reduction in electricity consumption by almost 50% while maintaining the capacity of cold generation

Keywords: quick freezing, food products, automation of technological lines, improvement of automatic control

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1. Introduction

Freezing over the past century has become one of the most popular technological processes that enable long-term preservation of freshness and nutritional value of various biological products.

Information analysis indicates the active intensive development of the modern global market for frozen products. The most developed countries occupy a particularly significant place in this segment. In particular, leaders in the consumption of such products are developed European countries: the consumption level exceeds 100 kg per year per capita [1].

Ukraine is a powerful exporter of frozen products to the European Union. For example, according to statistics, in 2021, about 80% of Ukrainian horticultural products were exported, and revenue from exports of frozen fruits alone amounted to about USD 200 million [2]. The geography of exports of this type of product is also expanding intensively.

The export potential of this industry in Ukraine is influenced by various factors and problems. Among the main ones are a large share of manual labor; lack of sufficient financial investments and capital investments in the development of the industry, high energy consumption, significant cost of organizational measures (certification, advertising), etc. The solution to the main problems is closely related to the design of modern equipment and technological processes for freezing food products. Therefore, research into the impact of improving technical equipment for freezing and automatic control modes of the corresponding technological processes is relevant.

2. Literature review and problem statement

The freezing technology is based on the processes of rapid freezing of food products using special chambers. The focus of scientific research in this area is on the features of the relevant equipment and technological processes and their impact on the quality indicators of frozen products. Among the literary sources, papers [3, 4] are noteworthy. Their authors report detailed studies on the main problems in the development of food freezing technologies and promising ways to solve them. In particular, it is shown that the peculiarity of shock freezing, unlike other technological processes, is the duration of freezing less than 30 minutes with the final product reaching temperatures of up to –30°C. However, the issues of reducing the specific electricity consumption per unit of frozen products for different types of existing equipment remain unresolved. This is due to both the technical parameters of the equipment of technological lines and the shortcomings of information systems for controlling technological modes of freezing. One of the ways to overcome such difficulties is to use existing freezers after retrofitting them with new energy-saving refrigeration equipment. The results of analyzing the use of such an approach are given in study [5]. At the same time, the need for serious investments to update the equipment is noted, which in volume are close to the option of purchasing new modern equipment. For the small business sector, such investments may be limited. This allows us to argue that for small enterprises it is advisable to study the possibilities of such modernization of refrigeration technological lines that does not require a complete replacement of the basic equipment, which has a significant unexhausted depreciation resource.

In papers [5, 6] it is shown that refrigeration systems can be divided into three basic types: stationary, dynamic, and cryogenic freezing. But for all types of such equipment, the issue of taking into account the physicochemical properties of a specific frozen product when automatically determining the freezing mode remains unresolved. This is due to the lack of effective control schemes that take into account these parameters, for example, the size of individual product fragments, their structure, water saturation, the value of thermal conductivity and heat capacity, etc. One way to overcome such difficulties is to manually set the freezing mode parameters for each type of food product. In particular, this approach is analyzed in [7] by using an example of conventional stationary freezers. However, this solution limits the possibilities of full automation of quick-freezing technological lines. This is especially true for dynamic freezing equipment [8], where the product is fed into the refrigeration chamber continuously using a special conveyor. This gives grounds to argue that it remains advisable to develop new algorithms for controlling automatic quick-freezing technological lines that promptly take into account both process modes and the properties of frozen products.

Analysis of the prospects for using new generation equipment for cryogenic freezing was conducted in study [9]. It was shown that cryogenic technological lines are fundamentally different from traditional refrigeration systems and make it possible to reduce the entire process to 10 minutes with the provision of a final product temperature of up to –100°C. However, the introduction of cryogenic systems to small businesses leaves unresolved the issues of finding significant investments and the complexity of servicing the installed equipment. The reasons are the general structure of cryogenic technological lines from liquid nitrogen generation systems, storage, transportation, and special freezers for blowing products with liquid nitrogen vapor. Thus, high quality indicators of frozen products in cryogenic units are achieved by a significant increase in financial costs for the purchase of equipment, training of service personnel, and maintenance of equipment. This necessitates the search for ways to combine the advantages of cryogenic freezing in terms of product quality with the use of more economically advantageous optimized automatic dynamic freezing lines based on operating unified refrigeration equipment.

All this gives grounds to argue that the task of reducing energy consumption per unit of product and decreasing the cost of servicing quick-freezing technological lines based on equipment with a long shelf life remains unresolved.

3. The aim and objectives of the study

The aim of our research is to determine ways to improve the dynamic shock freezing equipment and technological modes of its operation to reduce energy consumption and maintenance costs per unit weight of the initial product.

This will make it possible to reduce the cost of frozen food products and contribute to the saving of energy resources.

To achieve the goal, the following tasks were set:

– to investigate the impact of replacing the elements of the control system of dynamic shock freezing technological lines on their operational parameters and on the degree of their automation;

– to improve the process of automatic control of the operating modes of shock freezing equipment;

– to investigate the main operational parameters of the improved technological line.

4. The study materials and methods

The object of research is the technological lines of dynamic shock freezing of food products with a long shelf life. During this time, the technical base of technological lines has changed significantly in the direction of its digital transformation. Therefore, it is advisable to study the impact of digital modernization of technical and information systems of these lines on their operational parameters.

The research was conducted on the technological line of quick freezing at TOV Karpaten Bolet (Ukraine). The equipment of the line has already been in operation for almost 20 years, which caused its physical and, especially, moral aging and low efficiency of technological process control systems. In particular, the process of controlling the technological line under a semi-automatic mode was carried out by a special cabinet based on analog circuitry manufactured by EBG Electronic, VSE-MB (Germany) [10]. This electronic equipment allowed for the functioning of the technological line of freezing with screw compressors. Ammonia serves as the working fluid of the freezing equipment. For the research, a simplified functional diagram of this line was reproduced, which is shown in Fig. 1. This diagram shows only those elements of the production line that were subjected to modernization and automation of control in our study.

According to Fig. 1, the main equipment of the technological line includes the following basic components:

- a pumping and circulation station to maintain the required amount of working fluid in the cooling system;
- screw compressors for implementing a two-stage thermodynamic freezing cycle;
- a chiller with a pipe cooling system;
- a freezer with a blower fan module;
- a conveyor for feeding products into the freezing chamber;
- a condenser-cooling tower;
- a priority receiver with a buffer tank;
- a module for drying the working fluid from water and cleaning it from air;
- valves for manual control of the technological line;
- analog control valves of the AUMA SAN 07.1 type;
- analog sensors of various types and designs.
- an electronic analog control module for the screw compressor.

Additionally, the line is equipped with a pumpless water cooling system with a working cycle at an ammonia boiling point of –3°C. The purpose of this system is to obtain cold water, which is used to cool the corresponding technological equipment of the refrigeration plant.

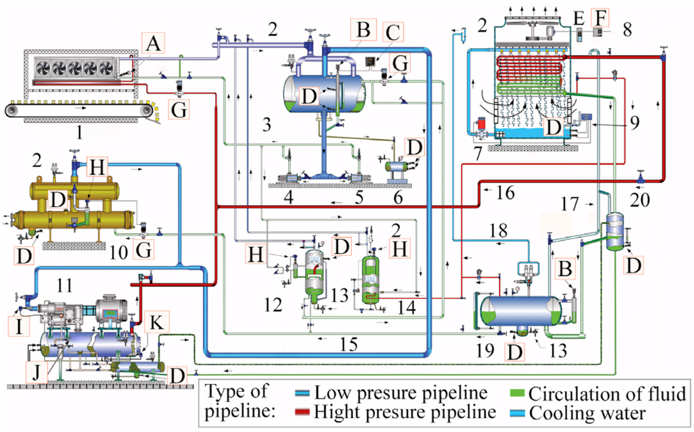

Fig. 1. Combined structural diagram of the shock freezing process line before modernization (1 – freezer, 2 – discharge to the atmosphere, 3 – pump circulation station, 4 – ammonia pump 1, 5 – ammonia pump 2, 6 – oil sump, 7 – condenser/cooling tower, 8 – cooling control module, 9 – water level control module, 10 – chiller with heat exchanger, 11 – screw compressor, 12 – working fluid dryer module, 13 – shut-off valve, 14 – air separator, 15 – liquefaction line, 16 – hot gas line, 17 – balancing line, 18 – emergency discharge line, 19 – ballast tank, 20 – priority receiver, A, B, C, H – sensors for monitoring the level of liquefied ammonia of various types in different elements of the equipment, D – liquid level switches, E – cooling fan frequency converter, F – cooling tower control unit, G – solenoid valves, I – compressor protection sensors, J, K – oil level sensors in gaseous ammonia)

The main equipment of the technological line can provide two basic modes:

- shock freezing with a working cycle at an ammonia boiling point of about –25°C;
- ordinary slow freezing with a working cycle with an ammonia boiling point of about –13°C.

The basic technical parameters of the studied dynamic shock freezing line are as follows:

- total mass of the working medium in the system – 30 tons;
- specific average power consumption of electricity per ton of product (dumplings) – 270 kWh;
- maximum power of cold generation – 520 kWh;
- the average coefficient of conversion of electrical energy into refrigeration energy [11] under a standard operating mode of the two-stage compressor system is 1.6;
- the number of service personnel is 3 people.

The parameters of the electrical power supply of the process line for one compressor with a three-phase AC motor are as follows:

- motor power – 200 kW;
- operating voltage – 380 V;
- motor operating current – up to 400 A;
- starting current – up to 800 A;
- reactive power factor cos(φ) – about 0.85.

The parameters of the process modes were studied during the regular operation of the process line to determine the influence of the basic parameters of the freezing process: working fluid pressure, working fluid temperature, and process fluid level. These parameters have the greatest impact on the technical and economic indicators of the shock freezing process line.

For the studies, Danfoss AKS 32 FS working fluid pressure sensors with a normalized measurement error of ± 0.3% were introduced into the compressor discharge channels in addition to the regular analog Mertik sensors. These sensors measured the suction pressure p at the inlet of the receivers after the process of throttling the liquid refrigerant with the corresponding valves. In the course of experimental studies, the pressure values p and thermo-EMF of platinum thermocouples e in the refrigerant discharge lines were measured at the moments of the operator's signals about the transition from one mode to another. At the same time, the SDS 1052 digital oscilloscope recorded the oscillograms of signals from standard sensors at the corresponding analog inputs of the control system. Manual control of transitions between modes requires operators to perform several operations with valves. Therefore, the time intervals τ that were spent by operators on these operations were also measured.

According to the results of measurements during the implementation of seven cycles of technological mode changes by the equipment, the average values were calculated:

- deviations Δp of the actual values of the suction pressure and the EMF of the thermocouple Δe from the optimal ones;
- hysteresis Δg of the pressure and EMF values of the thermocouples when switching to a certain mode and when leaving it;
- time interval Δt from the achievement of the optimal values by the specified parameters until the moment of the control system's reaction to changes in this parameter;

– maximum amplitudes u of low-frequency interference at the moments of switching from one mode to another.

The improvement of the technological line control system was carried out using the modern LOGOSoftComfort 8.0 computer shell.

Experimental studies of the technical operational parameters of the technological line after modernization were carried out during 14 hours of line operation under a standard mode of production of dumplings frozen to –10°C. In the process of research, using standard devices of the energy system of the technological line (dial ammeters and voltmeters and a meter of active and reactive power), the following were determined:

– starting currents of compressor motors;

– average operating currents of compressor motors;

– average reactive power factor cos(φ);

– specific power consumption of electricity per ton of product.

To accurately determine the coefficient η of the conversion of electrical energy into cold energy of the technological line, experimental measurements using a complex methodology are necessary [11]. Therefore, the value of this coefficient is approximately estimated based on the results of comparing the total consumed electrical power of the technological line for the production of one ton of dumplings before modernization and after modernization.

5. Results of research on the impact of technical modernization and improvement of the control scheme on the parameters of the technological line

5. 1. Determining directions for replacing elements of the quick-freezing line with modern devices

As a result of experimental studies on the functioning of the equipment under various technological modes, it was found that the input information channels of the automatic control system are built on the basis of the following analog industrial devices:

– manometric pressure sensors with electrical contact groups of the type Typ:612.11;

– differential pressure sensors of the type Typ:DR665.10;

– temperature sensors of the type Pt100;

– relay-type working fluid level sensors.

At the output of all sensors, analog output signals are formed, which are processed by analog transistor circuits of the electronic module. In this case, the values of the control signals for the automatic control system are set by the output voltages of these sensors. At the same time, the optimality of the freezing modes can be more accurately controlled by the values of the pressures and temperatures of the working fluid in the mains of the technological line. The results of experimental measurements of these parameters in several sections of highways at different stages of the technological process are given in Table 1.

In the process of analyzing the research results, the obtained experimental data in Table 1 were averaged. The calculated average parameters of transitions between the modes of the technological line are given in Table 2.

The interference pulse amplitudes given in Table 2 were determined at the input of the corresponding analog parameter control circuit by the electronic module at the moments of switching on and off of powerful screw compressor engines and other power equipment. The delay time was measured as the interval between the moment the corresponding physical parameter reached the switching limit value until the moment the control system actually switched the equipment operating mode.

Table 1

Readings of technological parameter sensors when changing equipment operating modes in seven operating cycles

Measurement event	Stage –13°C			Stage –25°C		
	p, kPa	e, mV	τ, s	p, kPa	e, mV	τ, s
Opening the manual valve for pumping the working fluid into the main by the compressor	432	8	440	353	10	510
	417	11	560	348	7	470
	426	10	670	335	5	520
	443	9	610	421	8	590
	405	12	720	396	7	390
	428	9	380	358	10	430
	416	10	660	428	10	460
Opening the manual valve of the freezing process	247	13	510	143	11	460
	252	10	470	151	9	430
	225	9	520	148	8	420
	261	11	590	152	13	360
	253	8	390	126	10	440
	239	11	430	138	11	450
	228	12	460	145	11	400
Manual valve switching when switching on another stage	213	12	450	142	9	410
	231	9	360	135	11	380
	239	13	490	122	14	370
	225	12	310	126	10	310
	237	12	280	143	11	390
	238	10	330	137	12	400
	215	14	470	125	12	360

Table 2

Averaged parameters of accuracy and reliability in controlling physical and technological parameters of the shock freezing line before modernization

Sensor type	Average suction pressure deviation Δp	Average suction pressure hysteresis Δg	Average delay time interval Δt, s	Average amplitude of low-frequency switching noise, V
Mertik-612.11	to 10 kPa	to 16 kPa	to 600 s	to 0.5
MertikDr-665.10	to 7 kPa	to 11 kPa	to 500 s	to 0.5
Pt100- 7400	to 2 mV	to 3 mV	to 400 s	–

To significantly improve the parameters of the automatic control and management system, all analog sensors of the working fluid mains were replaced with modern industrial components with digital output signals. At the same time, additional pressure, temperature, and level sensors of technological fluids were installed to expand the functions of the automatic control system. The type of sensors used, as well as their basic parameters, are given in Table 3.

Table 3

Parameters of digital sensors used for improving the technological line [12]

Sensor type	Sensor parameters
Pressure and vacuum sensors Danfoss AKS 32 FS type	Normalized output signal of constant voltage in the range from 0 V to 10 V. Relative error ± 0.3%. Hysteresis and repeatability – no more than ± 0.1%
Temperature sensors Danfoss MBT 5250 Pt 100 and Pt 1000 type	Measuring range from –50°C to +200°C. Sensor type EN 60751. Class B
Liquid level sensor HBLC/C-NH3-3.1-2; HBLT-WIRE-2 and HBLT-A1-8	Operating temperature range from –40°C to +70°C. Normalized DC voltage output signal in the range from 4 mA to 20 mA. Maximum pressure 10 MPa
Emergency liquid level sensors HBSR-PNP/NO-2	Operating temperature range from –40°C to +50°C. Maximum pressure 10 MPa. Normalized output signal – transistor logic standard (PNP or NPN)
Compressor protection sensors HBCP-1.5-2	Operating temperature range from 0°C to +50°C. Normalized DC voltage output signal in the range from 4 mA to 20 mA
Differential pressure switch MP-55A	Operating temperature range from 0°C to +50°C

All sensors listed in Table 3 are designed for placement in a chemically aggressive ammonia environment and have information output ports made according to modern industrial standards. At the same time, the output signals correspond with high accuracy to the values of real physical parameters of the working fluid: temperature, pressure and level.

To significantly increase the degree of automation of the shock freezing process line, most of the manually operated valves were replaced with electromagnetic valves of the Danfoss EVRA 25 type [13]. Their throughput is 10 m^3/h, and the maximum pressure is 4.2 MPa. The temperature range of the working medium is from –40°C to +105°C.

In main lines with large refrigerant flows through the freezing line, standard manual valves were upgraded with an automatic drive with an asynchronous electric motor and an industrial worm gearbox TCM063U100 (type AUMA SAN 07.1). Such motorized valves were also equipped with sensors for automatic control of the valve position with an output signal of 4–20 mA and contactless sensors of the end position "Open/Closed". The automatic electric drive provided the operating cycles "open-closed" and "closed-open" for 30 s.

The implementation of the above set of modernization operations allowed us to fully automate the shock freezing technological line. The structural and functional diagram of the automatic functioning systems of the modernized technological line is shown in Fig. 2.

The diagram in Fig. 2 shows only those elements of the process line that are monitored and controlled by the advanced automatic control system. These include:

– valves and controlled valves with an electric drive marked with numbers from 1 to 8;

– black lines – digital and analog communication channels with PLC;

– yellow lines – flows of liquefied ammonia of circulation receivers 1 and 2;

– orange – return flows of spent refrigerant to linear receivers;

– blue – flows of liquefied refrigerant to compressors;

– red – flows of compressed ammonia;

– green – flows of supply, cooling, and recirculation of oil for compressors;

– light blue – flows of water for cooling equipment and working fluids of the process line.

Before the modernization, the automatic mode of operation of the technological line was based only on analog sensors P1, P2, T3, and T5 (Fig. 2), which were replaced by digital ones in the process of improvement. Other sensors served only for monitoring the equipment status by three operators and for manual control over the technological equipment by operators. After the modernization, according to Fig. 2, the basic parameters of all systems of the automatic technological line of shock freezing are used as controls. This is ensured by introducing sensors S1–S4, P3, dP, T1, T2, T4, T6, T7, and valves 4, 5, "B", "H" into the automatic control system (Fig. 2).

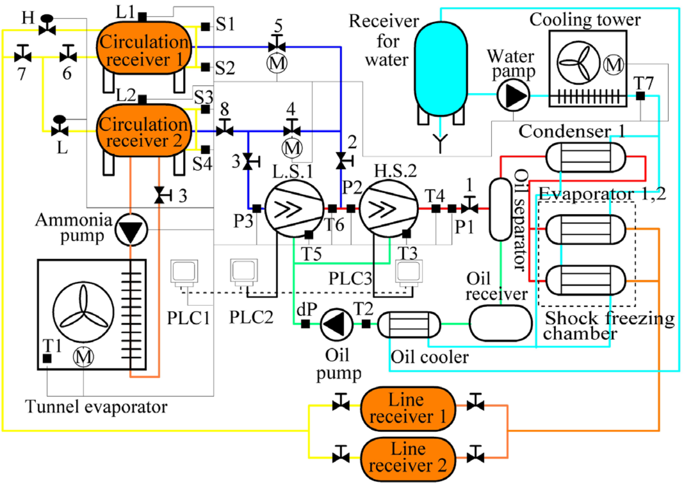

Fig. 2. Structural and functional diagram of automatic systems of the shock freezing line: PLC – industrial logic controllers; T – temperature sensors; P – pressure sensors; dP – differential pressure sensor; S – liquid level sensors; L – emergency liquid level sensors; B and H – controlled solenoid valves of the compressors of the upper and lower cooling stages

5. 2. Improving the automatic control scheme of the shock freezing technological process

Considering the complex algorithm of automatic operation of a multi-element shock freezing line, in the process of its improvement, three programmable logic controllers (PLCs) were also introduced into the control system (Fig. 2). Two PLCs ensured automatic operation of the refrigeration compressors, and the third PLC served the main functional units of the entire technological line (Fig. 2). When forming the topology of the control system, a network solution based on the Ethernet standard was used.

The control system of the modernized line should ensure coordinated interaction of more than 30 different components (sensors, valves, actuators, etc.). To increase the reliability of the control process and simplify the program of each PLC, several expansion modules of digital and analog inputs/outputs were introduced into the control system. The types and main parameters of the elements and modules of the automatic control system are given in Table 4.

Table 4

Main components of the control system and their basic parameters [14]

Component type	Component parameters
PLC Siemens LOGO 8! Basic Modules	LOGO!12/24RCE, 8DI(4AI)/4DO, 400 Blocks
Digital I/O expansion modules	LOGO! DM16 24 Exp. mod., 4 MW, 8DI/8DO
Analog input expansion modules	LOGO! AM2 RDT, 2AI, –50..+200DECR/C
Analog input expansion modules	LOGO! AM2 AQ, 2AQ, 0 – 10V, 0/4 –20 mA
Text Display TDE via Ethernet	LOGO! TDE, 6 lines 20 ch
Power supply module	SIPLUS LOGO! POWER 24 V 4 A

According to Table 4, all information about the current state and processes of the technological line operation was displayed on the operator's text-symbol display of the LOGO! TDE type. The power supply of the information components of the control system was provided by a special SIPLUS LOGO! source with an output voltage of 24 V.

The choice for research as the main control elements of the Siemens LOGO 8! PLC was dictated by the optimal combination of its functional and economic parameters. Analysis of the information flows that flow in the technological line reveals that their maintenance is fully provided by the functionality available in the Siemens LOGO 8! and LOGO! 8 TDE devices. Since it is planned to use the modernized line under different modes, including when using each compressor alone, it is logical to divide the control system into three independent modules. The basis of each of them is a separate PLC.

Modernization of the shock freezing technological line is also possible using more powerful information equipment, for example, SIMATIC S7-1200 controllers and SIMATIC HMI KTP400 operator panel. However, such a technical solution requires a significant increase in the research budget.

Thus, the combination of three Siemens LOGO 8! PLCs into a single process control system using the built-in Ethernet communication interface makes it possible to fully solve the tasks set in our study. From a commercial point of view, it is also important that the selected information equipment is provided with full technical and software support from the manufacturer.

For the modernized technological line, a functional scheme for automatic control of the equipment under different operating modes was designed. This stage of research was carried out using the modern computer shell LOGOSoftComfort 8.0. A feature of this shell is the representation of the control process in the form of logical operations. During the experimental tests of the modernized technological line, the functional scheme was improved to ensure both the maximum speed of shock freezing and to take into account the type of frozen product in accordance with [15].

At the same time, the improvement process achieved the most economical use of electrical energy by the equipment of the technological line at different stages of the freezing process. The final simplified version of the designed and improved control scheme for one controller for controlling the compressor unit of the first stage of freezing is shown in Fig. 3.

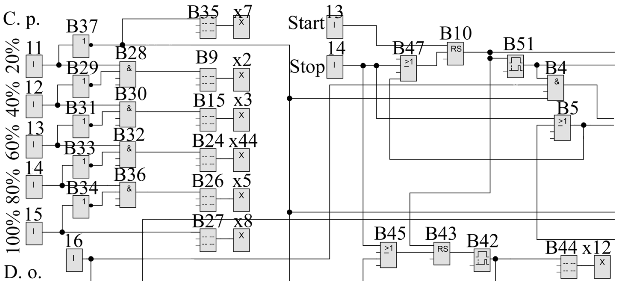

Fig. 3. Screenshot of the LOGOSoftComfort 8.0 software package, part of the functional diagram of the programmable logic controller for controlling one of the cooling stages of the compressor unit

The complete functional diagram contains two modules for controlling the operating modes of two compressors by two independent PLCs and one module for controlling other equipment of the process line based on a separate PLC.

5. 3. Experimental studies on the operational parameters of the modernized technological line

Experimental studies conducted using the above-described methodology during 14 hours of operation of the technological line in the quick-freezing cycle of dumplings produced the results given in Table 5.

The technical and economic parameters of the operation of the automatic technological line, given in Table 5, in an integrated form reflect the impact of both the modernization of its structural elements and the improvement of the freezing process control system.

Table 5

Operational parameters of the shock freezing process line after its modernization and automation

Parameter	Parameter value before automation	Parameter value after automation
Average reactive power factor $\cos(\varphi)$	0.85	0.91
Starting currents of compressor motors	Around 800 A	Less than 500 A
Average operating currents of compressor motors	Around 400 A	Less than 200 A
Specific power consumption of electricity per ton of product (dumplings)	270 kW · h	Not exceeding 150 kW · h
Coefficient of conversion of electrical energy into refrigeration energy	1.7	2.9
Number of service personnel	3	1

6. Discussion of the results of investigating the impact of technical and informational modernization on the operational parameters of the technological line

The results of our research of the existing equipment for a shock freezing technological line showed (Tables 1, 2) that the analog channels of control over technological modes have significant shortcomings. According to the physical and technical parameters of the cooling system, the optimal working fluid pressure of 0.257 MPa for the lower stage and 0.150 MPa for the upper freezing stage should be maintained in the refrigerant throttling zone [10]. These values correspond to the refrigerant boiling points of –13°C and –25°C. When maintaining the specified pressure values, the refrigerant boiling point is self-maintained in the supply lines to the freezing chamber.

The main control parameters for manual control of the freezing process before improvement were the working fluid temperature in the compressor discharge zone and the measured pressures in the throttling zones of both cooling stages. These three parameters were automatically monitored by the control system for analog sensor signals, and, at their corresponding values, information was provided to the operators. The subsequent control of the technological line was carried out manually by switching the necessary system of valves and gates.

The results given in Table 2 show that the input information analog channels of the manual control system are characterized by low accuracy and reproducibility. First of all, this concerns significant deviations Δp of real physical quantities from the normalized technological parameters, at which the automatic control of this parameter should be triggered (Tables 1, 2). As a result, the processes of switching the functioning of the equipment from one technological mode to another were delayed in time. In particular, changes in the pressure of the working fluid by the deviation value $\Delta = 10$ kPa (Table 2) required about 10 minutes of additional operation of the compressor equipment. With such significant delays in transitions between different technological modes, the equipment operates unproductively with unjustified losses of electricity and additional depreciation of the equipment. Similar losses are also caused by the presence of significant hysteresis of the control system operation parameters when switching to operating modes with one or two freezing stages. In addition, the described deviations affect the cooling rate of products in the freezing chamber, and, accordingly, the quality of the finished product.

In the process of experimental research, the main reasons for our results regarding the behavior of the analog control system were also revealed:

– physical aging of the sensors of analog sensors;

– shift of the operating points of the transistors of the input channels of the electronic control circuit;

– low noise immunity of the communication lines of the sensors with the control circuits and the control circuits themselves.

At the same time, the third reason was especially intensively manifested in the switching modes of large electrical capacities on the equipment of the technological line. A comprehensive analysis of our results determined the strategy for technical improvement of the technological line – replacement of all sensors and control electronics with modern digital devices (Table 3).

The functioning of the technological line before modernization was enabled by 3 people. This is due to the need for constant monitoring and control operations of a complex refrigeration system consisting of two screw compressors and about 20 manual valves and gates when switching from one technological mode to another. The study of the features of the interface of interaction between operators and equipment also revealed a significant influence of the human factor on the control process. Analysis of the results allowed us to identify two main trends in manual control of the production line.

Firstly, it is inconvenient for the perception of information on the display in the form of a set of 16 green and red light indicators. At the same time, this display is integrated into the general equipment control panel, on which manual switches and buttons are located. In general, the structure of the information and control panel is very inconvenient for operators to process information and make appropriate decisions quickly.

Secondly, the maintenance of the existing technological line before the modernization was entrusted to three operators. The main responsibilities of one of them included continuous monitoring of the information board signals and manual control of the panel switches. The other two operators were responsible for controlling the equipment and transferring the entire system of manual controls to those positions that ensured the implementation of the required stage of the technological process. At the same time, the exchange of information between the operators took place visually and by voice commands.

With the above features of the machine-human interface, the quality and safety of the control process significantly depended on the knowledge, skills, and professional actions of the operators. In many situations, switching equipment from one technological mode to another was carried out during large time intervals between the moment of changing the signals of the control system and the end of the corresponding actions of the operators. In some cases, such delays could reach 10 minutes.

Our analysis revealed the need for the second direction in improving the technological line – the introduction of new control and management elements that allow for more complete automation of technological processes. Since the basic equipment of the process line remained unchanged, the operation of the automatic control system should essentially reproduce the order of actions of the operators. To this end, the manual shut-off valves of the main working fluid flow lines were equipped with an electric drive, and the manual valves were replaced with electromagnetic ones.

The installed automatic valves "B" and "H" (Fig. 2) were especially important for automating the technological mode of freezing. They are designed to control the level of filling with the working fluid of the circulation receivers 1 and 2 of the compressors of both cooling stages. A significant increase in the level of the working fluid increases the intensity of water hammer in the compressor, and a decrease in the level causes cavitation in the pumps of the refrigerant circulation system. The liquid level in the receivers is constantly changing in the process of changing the thermal load of the refrigeration equipment. Therefore, this parameter must be constantly maintained in the optimal range of values for reliable operation of the cooling system. To automate the process of controlling the refrigerant level, the float control sensor was replaced with digital devices S1–S4 with the introduction of automatic valves and valves into the mains. During experimental studies, the minimum filling level of the receivers was set at about 30% of the total capacity. At this level of refrigerant, the necessary high speed of freezing of products was ensured without additional electricity consumption for the circulation of the refrigerant.

According to the results of studies of the operating modes of electrically driven valves, important features of the process of controlling them were established. In particular, this is the need to regulate the optimal flow of the working fluid through the mains under different operating modes of the compressor equipment, especially at the stages of starting and stopping the compressors. installation). It was also important to establish the optimal speeds of opening and closing the mains by valves to avoid water hammer and soften the starting modes of the compressor motors. As a result, the automatic control system provided for intervals of full valve operation of about 30 s.

Automation of the technological line also required the installation of a new equipment-operator interface system. This system was designed on the basis of a multifunctional text-symbol display, the exchange of information with which is carried out on the basis of the Ethernet protocol (Table 4).

In the course of our research, the need to install additional sensors was also identified. In particular, this is an additional differential oil pressure switch *dP* in the lubrication lines of the mechanical parts of the equipment (Fig. 2). This sensor makes it possible to effectively diagnose the condition of the cleaning filter of the lubrication system – a large pressure difference measured by such a sensor signals the need to replace the oil filter. The introduction of additional sensors also allowed the software to significantly increase both the level of safety of the equipment and the informativeness of messages on the installed operator screen.

The introduction of a number of digital sensors, new control elements, and information display required a radical change in the program for automatic control over quick-freezing equipment. This stage of the research was carried out on the basis of the LOGOSoftComfort 8.0 technical automation software platform. When developing a program in this computer shell, the code for the PLC is compiled without writing a corresponding program in one of the programming languages. For this purpose, the devices for controlling the parameters of the technological process are represented as generators of information bits, and the operations performed are specified in the form of corresponding logical functions. On the LOGOSoftComfort 8.0 desktop, logical functions that must be performed in the process of automatic control, were displayed by icons of logical elements. In Fig. 3, such a representation is shown in the form of a desktop screen with a designed functional diagram of the PLC operation to control one of the stages of cooling of the compressor unit. Similar software products were developed to control the second stage of cooling and to control other systems of the technological line.

When constructing the functional diagram and program, additional tasks were also solved to improve the process of automatic control of the operating modes of the shock freezing equipment:

1. Ensuring reliable automation of the entire technological process of quick freezing of products. After the equipment was put into operation, operator intervention was necessary only in the event of emergencies, for example, a delay in the supply of products to the freezer or technical failures of certain equipment.

2. The ability of the operator to select one of the fixed freezing modes for various products (berries, meat products, semi-finished products, etc.) based on their thermal conductivity, percentage of water content and size of individual products. For this purpose, the functional control scheme provides for branching the program to execute three different modes.

3. Simplicity of the process of transferring the technological line to different modes of its operation. For this purpose, the operator only needs to change the appropriate settings of several parameters on the text-symbol display using the appropriate keys. In particular, for the flow of small-sized products in the freezer, the operator should reduce the freezing temperature since such products have time to freeze during passage through the chamber and at a low temperature. Such changes in the technological process allow for significant savings in energy resources.

4. Introduction into the functional diagram of the program of data processing operations from additionally installed sensors in order to expand the service functions of the process line automation system:

– increased informativeness of the text-symbol display, on the screen of which the states of important equipment elements and parameters of technological flows in all main lines (refrigerant, water, gas mixtures, oil, etc.) are displayed;

– self-diagnosis of the process line equipment before its start and during its operation;

– warning the operator about approaching the limit or emergency technological modes of operation of the equipment;

– rapid automatic response to abnormal events and emergencies with the safest steps of blocking individual equipment elements, localization and exit from abnormal situations up to a complete stop of the process line.

5. Transparency and convenience of perception by the operator of information displayed on the text-symbol display.

The results of our research of the equipment operation process after its technical improvement and adjustment of the parameters of the functional control scheme showed a decrease in the level of energy consumption by almost two times (Table 5). At the same time, the main factors influencing this indicator were identified:

– timely switching on and off of the equipment water cooling pump, cooling tower fans and oil circulation pump in accordance with the optimal operating modes of various refrigeration equipment;

– slow modes of opening and closing of the electromagnetic valves of the compressor stages in accordance with changes in the working fluid pressure in the mains and the refrigerant level in the receivers. Under such modes, the engine power could be reduced by up to 50%;

– switching on of compressors of both stages of cooling after the working fluid reaches the minimum permissible pressures, due to which the starting currents were halved;

– continuous monitoring and maintenance of the temperature in the freezer in the product freezing zone at the optimal level, avoiding excessive load on the compressors;

– imely switching of equipment to different operating modes.

The last of the above points turned out to be the factor that gives the most significant effect of saving electricity while maintaining the cooling capacity and volume of the initial products of the freezing technological line. To achieve a temperature in the freezer to –20°C, it is enough to operate only the compressor of the lower cooling stage. To ensure temperatures in the freezer to –30°C, it was necessary to additionally activate the compressor of the second cooling stage.

Experimental studies on the automatic mode of operation of the technological line also showed its individual shortcomings. The main one is the insufficient coordination of the automatic functioning of various systems of the technological line: cold generation, cooling tower and conveyor for feeding products into the freezer. At certain stages of the technological process, reliable cooling of compressors at their peak loads was disrupted due to insufficiently cooled water coming from the cooling tower. In such cases, the compressor performance is automatically reduced without appropriate regulation of the product feed rate to the freezer. Thus, the optimal shock freezing mode is disrupted. To eliminate this drawback, it is necessary to conduct research on expanding the functional scheme and automatic control program for closer interaction of all equipment of the technological line. The introduction of software modules into the functional control scheme to prevent negative consequences from incorrect actions of the operator and personnel working on the technological line remains relevant.

Automatic smooth control over the working fluid parameters in the cooling system mains also provides more optimal start and stop modes of compressors. As a result, the starting currents of their electric motors are almost halved (Table 5). In addition, the operation of compressor equipment under the optimal mode ensures a reduction in electricity quality losses by increasing the reactive power factor cos(φ) (Table 5).

In the case of the production of dumplings pre-cooled to +5°C, the process of freezing 1 ton of products to –20°C lasted on average 1.5 hours, which corresponds to an average productivity of about 10 kg per minute. At the same time, the total time for a separate portion of products to pass through the entire freezer was about 30 minutes. Of these, about 15 minutes were spent on the process of cooling to 0°C and freezing to –5°C, and the remaining 15 minutes were spent on the process of cooling to the final set temperature.

In the process of research, a significant area was also established for increasing the economic efficiency of the technological line. It is associated with the use of thermal energy, which is dissipated by the cooling tower into the atmosphere, to supply the enterprise with hot water with a temperature of up to +80°C. According to the technical parameters of the technological line, this is the maximum permissible temperature at the outlet of the water cooling system of the freezing equipment.

Observation of the functioning of the modernized technological line under an automatic mode showed minimal dependence of the equipment operation on the human factor with the possibility of reducing the number of service personnel to one operator.

The solutions proposed in this study allow small businesses to modernize their existing quick-freezing equipment at minimal investment costs. The use of the directions for improving the technological line studied in our paper allows for the automation of freezing processes with equal consideration of both the economic efficiency of production and product quality. In contrast, study [15] notes the main focus of manufacturers of modern refrigeration equipment on achieving technical and economic efficiency, while product quality indicators are "laid" in the averaged parameters of the technological process.

Analysis reveals that the solutions adopted in the process of re-equipping the equipment and the experimental results obtained in this process provide a solution to the problem of technical improvement of the quick-freezing technological line set out in the study. At the same time, a number of limitations of this study were also identified – individual elements of the equipment were not updated within the framework of this work. In particular, this concerns the functioning of cooling tower components, conveyors for feeding products into the freezer and collecting frozen products, working fluid and water mains, and the expansion of the functions of controlling the freezing process in the freezer. Therefore, it becomes important to expand research in this area in the future.

In addition, an important area for future research on this topic is to determine the dependence of the time for reaching a temperature of about –5°C directly inside the product. This time significantly depends on the size and type of food products. This effect is due to different values of thermal conductivity and the degree of water saturation of the components of different products. Accurate consideration of such parameters will make it possible to set the maximum speed of movement of specific products in the freezer and accordingly increase their output at a given energy cost.

To accurately determine coefficient η of the conversion of electrical energy into the energy of cold formation of the technological line, experimental measurements using a complex method are required [11]. Therefore, the value of this coefficient given in Table 4 is estimated based on the results of comparing the total consumed electrical power of the technological line for the production of one ton of dumplings. Before the modernization, it was equal to about 270 kWh, and after the modernization it decreased to 150 kWh (Table 4). If we take into account that before the modernization the value was $\eta = 1.6$, then the effect of reducing the specific power of the entire equipment achieved in the study can be ensured with a value of η of about 2.9.

7. Conclusions

1. When improving and modernizing automatic dynamic shock freezing technological lines, the maximum efficiency of the equipment is achieved by using digital sensors with high accuracy of measuring technological parameters. In this case, it is mandatory to use pressure and refrigerant level sensors in various elements of the equipment, temperature sensors of the working media of the freezing systems, water cooling, freezer, oil lubrication, etc. In the process of automation and improving the technical and economic indicators of quick-freezing equipment, an important role is played by the use of controlled valves and gates with an electric drive in all lines of the technological line. Such an organization of control and management technical equipment makes it possible to automatically perform technological freezing operations taking into account both the indicators of preserving the quality of a particular product and the most efficient use of energy resources. Installing a wide range of sensors and controlled valves and gates also ensures an increase in the level of safety of the automatic operation of the equipment and improves the informativeness of the equipment-operator interface.

2. Improvement of information collection subsystems and executive devices allowed us to develop an expanded functional scheme of automatic control over the shock freezing technological process based on three PLCs. PLC control programs designed on the basis of this functional scheme are focused on the implementation of a scenario of the automatic freezing process in which:

– the nutritional values of a specific type of frozen product are maximally preserved;

– the most economical consumption of energy resources is ensured by all components of the technological line;

– the process of controlling the operation of the equipment by the operator is facilitated;

– the level of safety during the operation of the technological line is increased;

– the possibility of switching to manual control over the technological line equipment is retained if such a need arises.

3. Our experimental studies on operational parameters for the improved automatic shock freezing technological line have shown minimal dependence of its functioning on the human factor with the possibility of servicing the equipment by one operator. The functional scheme and automatic control programs of the equipment ensured a reduction in the total energy consumption of the technological line by almost half while maintaining the performance of cold generation and the speed of freezing of products. At the same time, more flexible operating modes of the power electrical equipment of the compressors were achieved, which significantly increases their service life. The complex impact of improving the technical part and the functional control scheme with full automation of the shock freezing process also increased the level of self-diagnosis, safety, and environmental protection of the technological line.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the result reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Authors' contributions

Svitlana Baloha: Software, formal analysis, writing – review & editing; **Serhiy Buletsa**: Methodology, software, investigation; **Valentyn Ivanytsky**: Conceptualization, writing – original draft, project administration; **Viktor Kovtunenko**: Methodology, formal analysis, supervision; **Legeta Jaroslav**: Resources, writing – original draft, visualization; **Roman Meshko:** Conceptualization, validation, investigation; **Mykhaylo Ryaboshchuk**: Validation, investigation, resources.

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