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Development of an Energy Efficient Refrigeration Unit Using Carbon Dioxide as a Natural Refrigerant

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ABSTRACT

Refrigeration units, ubiquitous in various industrial applications, necessitate refrigerants for effective heat transfer. The end of service life for these agents, predominantly fluorocarbon-based, poses significant environmental hazards, necessitating safer alternatives. To mitigate fluorine-based environmental pollution, several solutions are under exploration, with a key proposal being the utilization of natural substances, such as carbon dioxide (R744), as refrigerants. This study introduces a novel design for a refrigeration unit operating on carbon dioxide. Distinctively, the proposed unit incorporates a series of nozzles in the refrigerator compartment that spray the refrigerant directly onto the food items, thereby expediting the cooling process. The operation principle of this unit, based on direct contact between carbon dioxide and the food products, is its primary novelty. A calculation technique is proposed for the selection of unit components, enhancing the cooling efficiency by facilitating direct heat exchange between the refrigerant and the product. The design includes a 3D model of the unit, developed in accordance with the sizes of currently manufactured equipment, and a layout that ensures mobility. The implementation of a recuperation principle in the unit allows a 20% reduction in refrigerant mass consumption, while the direct contact method increases the freezing rate by 30%. The proposed utilization of R744 as a refrigerant could significantly attenuate the emission of ozone-depleting substances, thereby contributing positively to the current environmental situation.

1. INTRODUCTION

Refrigeration units have become an indispensable part of contemporary living, consistently leveraged in the preservation, transportation, and storage of consumable products [1]. A key parameter, maintained assiduously during these processes, is temperature, modulated and controlled within refrigeration units [2-4].

Acting as devices designed for the reduction and maintenance of normalized temperatures, refrigeration units operate through heat exchange between the object to be cooled and the refrigerant. The majority of refrigerants currently marketed are chlorofluorocarbon (CFC)-based, including R12, R22, and R502. However, the long-term use of these CFC refrigerants has posed significant safety concerns [2]. The release of these gases into the atmosphere engenders a greenhouse effect, leading to the degradation of Earth's ozone layer [5]. This damaging effect can be attributed to the chlorine component of the refrigerants, which transforms ozone into oxygen upon interaction [4, 6, 7].

In response to these challenges, the scientific community has embarked on research aimed at preserving the Earth's ozone layer, focusing on the replacement of existing chlorine-based refrigerants with safer alternatives and the development of compatible refrigeration units [3, 8, 9].

Hence, numerous low-temperature units utilizing carbon dioxide as a refrigerant have been developed globally, including in Russia. Generally, these systems are sealed and exhibit several drawbacks, such as elevated pressures of up to 8 mPa, increased equipment costs by a factor of 1.5, the requirement for auxiliary equipment (e.g., high-pressure vessels, emergency relief valves), and extended freezing durations of up to 30% due to the absence of direct contact with the material [10]. Units operating on CO_2, based on the principle of direct contact between the refrigerant and the material, can mitigate some of these disadvantages. For instance, high pressures, additional equipment, and freezing time can be reduced, and a recirculation system can prevent CO_2 emission into the atmosphere.

Consequently, there is a current demand for the development of innovative cooling systems that operate using environmentally friendly refrigerants. This study aims to develop a novel refrigeration unit, providing a detailed description of its design and operational principle, which is premised on the direct contact of the refrigerant R744 with the product.

The refrigeration unit under development is designed to operate on carbon dioxide, a substance devoid of chlorine atoms, thereby minimizing the potential for ozone depletion (ODP) and global warming (GWP). This environmentally-friendly unit aligns with contemporary standards and requirements, making a significant contribution to the mitigation of ozone layer destruction and greenhouse effect exacerbation. Despite CO_2 being classified as a greenhouse gas, its use as a refrigerant, in lieu of hydrofluorocarbons, is projected to drastically decrease both direct greenhouse gas emissions due to leakage (given that HFCs possess a GWP thousands of times greater than CO_2) and indirect greenhouse gas emissions resultant from electricity generation.

2. METHODS

A schematic solution for the carbon dioxide refrigeration unit for contact freezing of products with CO_2 recirculation has been developed at Kemerovo State University.

The project of the refrigeration unit has been developed taking into account modern requirements for the design of refrigeration systems and following the design specification, current norms, rules, and State Standards of the Russian Federation (RF): PB 03-592-03 GOST 33662.2-2015 (ISO 5149-2:2014), GOST P 54381-2011, GOST EN 378-1-2014, GOST 32968-2014 [11, 12].

The program for the selection of Danfoss heat exchangers (Danfoss Heat Exchanger Calculation Tool) was used, and the dimensions of refrigeration equipment were taken from the official websites of manufacturers such as Bitzer, Emerson, Frigopoint, Cold Stream, and Polair.

The development of a schematic solution for a carbon dioxide refrigeration unit included the following stages:

The first stage of the work consisted of the development of the cycle of a three-stage refrigeration unit. In the next stage, the calculation and selection of refrigeration equipment were carried out using generally accepted methods, as well as modern software for the design of 2D and 3D refrigeration system models. At the next stage, a layout of a three-stage refrigeration unit for contact freezing with carbon dioxide recirculation was developed. In the following stage, a 3D model of the refrigeration unit was developed. At the final stage of the design, complex automation of the system was carried out, which allows for increasing the level of safety, energy efficiency, and optimization, as well as reducing the participation of people in the maintenance of the unit.

When developing 3D models of the refrigeration unit, we used AutoCAD three-dimensional computer-aided design and drawing systems. This program was chosen for system design because of its fairly informative interface and ability to develop 3D models that allow one to effectively work out the layout of the components of the designed installation.

3. EXPERIMENTAL PART

The first stage of the work consisted of the development of the cycle of a three-stage refrigeration unit. The main difference in the schematic diagram of the refrigeration unit is the use of the direct contact cycle of CO_2 with the product supplied for freezing. The essence of the device functionality is as follows: the refrigerating agent that circulates in the system, unlike existing closed-type systems, will interact with the product directly. After passing through the collector, CO_2 is fed into a series of nozzles and sprayed in the chamber, forming a snow-like layer on the product. Heat exchange with the product in the chamber is carried out through this layer. Snow-like carbon dioxide takes heat from the product, sublimates, and is sucked out by the compressor. The process is cyclical.

Since the cycle implies contact of the refrigerating agent with the product, this creates two radical design differences in the layout compared to the existing circuits. Firstly, there is no evaporator in the circuit. Secondly, a chamber capable of withstanding high pressure in the range of 4 to 5 MPa is needed.

The initial data for the design of the refrigeration unit were: Working substance (R744); Cooling capacity Q_0: (8.64) kW; Condensation temperature T_k: (25)°C; Boiling point T_0: (-45)°C.

When constructing a refrigeration unit cycle, intermediate pressures are selected so that the degree of pressure increase in the stages is equal [1, 5].

In the next stage, the calculation and selection of refrigeration equipment were carried out using generally accepted methods, as well as modern software for the design of 2D and 3D refrigeration system models. We also used:

ANSYS Fluent: Software for numerical modeling and simulation of various physical phenomena, including heat transfer and fluid dynamics. It can be used for the design and analysis of low-temperature plants.

Aspen HYSYS: Software for modeling and optimizing processes, including the design of chemical plants. It can be used for the development and optimization of low-temperature plants using safe refrigerants.

The results of the selection of equipment are summarized in Table 1.

Table 1. Explication of refrigeration equipment

No.	Name	Number
1	Emerson ZO104KCE compressor	2
2	Copeland ZO38AG compressor	1
3	Bitzer KO83RN heat exchanger	2
4	FP-OS(HP130)-5 oil separator	1
5	K073HP(P) shell-and-tube capacitor	1
6	FP-AS(HP90)-3 liquid separator	3
7	CS-LRH-25.0 receiver	1
8	Cold chamber	1

At the next stage, a layout of a three-stage refrigeration unit for contact freezing with carbon dioxide recirculation was developed, which is shown in Figure 1(a).

The principle of operation of the refrigeration unit is as follows: the first stage compressor unit (1) (ZO104KCE) sucks vapors from the liquid separator (12) (FP-AS(HP90)-3) and compresses the gas to the first intermediate pressure, which is equal to 2.57 MPa. The gas enters the heat exchanger (4) (K083PH), where its temperature drops to -15°C, after which it enters the compressor of the second stage (2) (ZO104KCE), where the gas is compressed to the second intermediate pressure (4.3 MPa). After that, the refrigerant moves to the heat exchanger (5) (K083PH), and then to the compressor of the third stage (3) (ZO38AG), where the gas is compressed to the condensation pressure. The superheated steam is sent to the oil separator (6) (FP-OS(HP130)-5), where the oil is separated from the vapors. The oil is separated and distributed between three compressors, having previously passed through oil filters. The hot vapors enter the water cooling condenser 7, where the vapors condense and the resulting liquid enters the liquid separator (8) (FP-AS(HP90)-3). The gaseous refrigerant is sent back to the compressor of the third stage (3). After that, the liquid refrigerant enters the liquid separator (9) (FP-AS(HP90)-3), where a similar process takes place. The liquid refrigerant enters the linear receiver (10) (FP-LR(HP90)-50), then enters the chamber (11), the process of throttling into the snow-like and gaseous phase and feeding into the cooled object takes place in the nozzles, the snow-like carbon dioxide sublimates into a gaseous state and is sucked by the compressor through filters and the liquid separator (12) (FP-AS(HP90)-3).

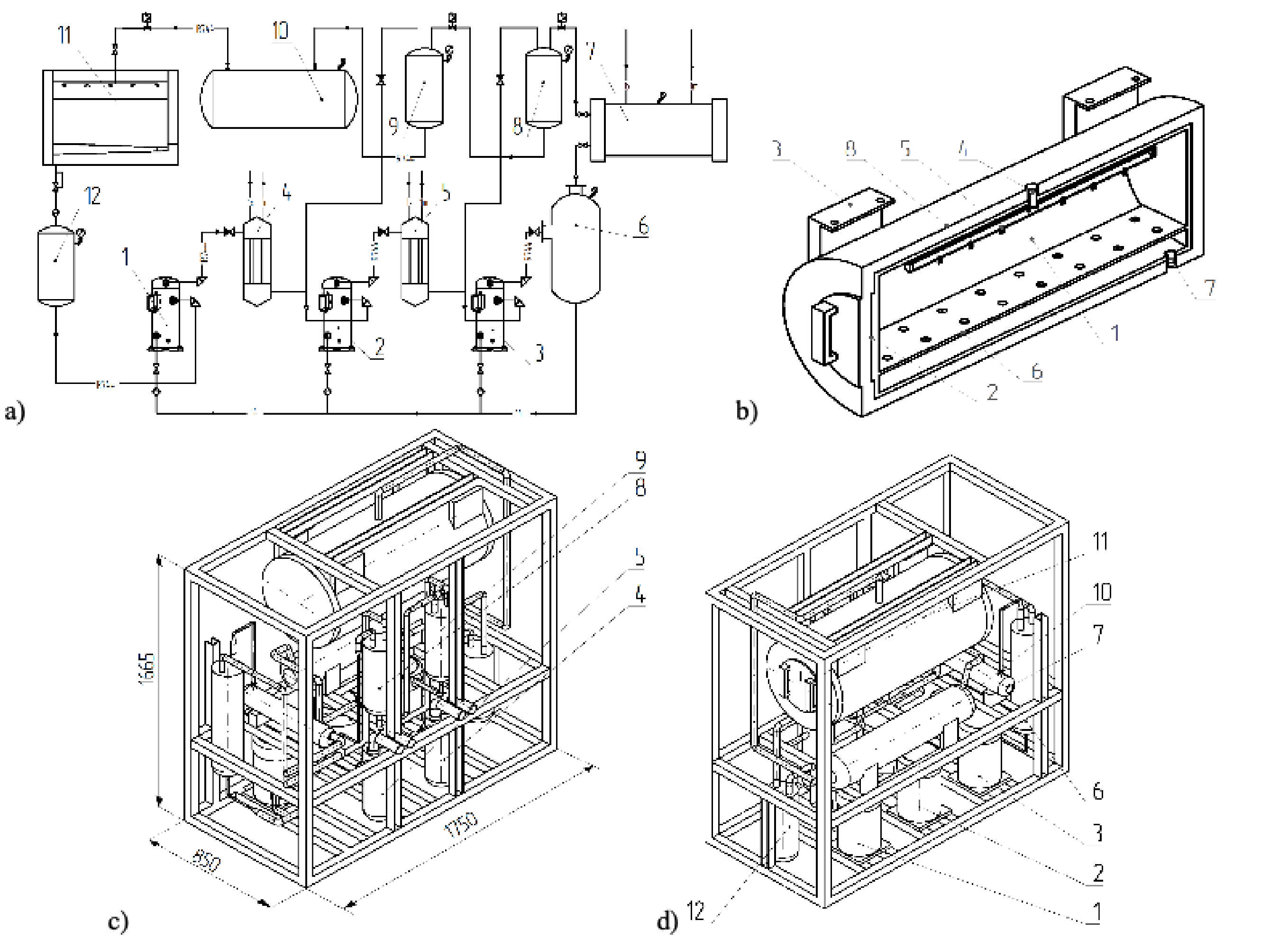
Since the principle of operation of the proposed refrigerating machine consists of direct contact of the refrigerating agent with the product, and the industry does not produce standard chambers for the implementation of the proposed principle, it was decided to design a refrigerating chamber capable of withstanding pressures in the range from 4 to 5 MPa.

Figure 1(b) shows the isometric projection of the refrigeration unit chamber. The chamber has a cylindrical shape and a diameter (D) of 430 mm (1). A window with D=300 mm is installed in the end wall for loading and unloading products (2). Clutches (3) are provided for attaching the chamber to the frame in the device. In the upper part of the chamber, there is a pipe with a D=20 mm (4), through which the refrigerating agent enters the inner volume of the chamber through nozzles (5) in the amount of 8 pieces with a D=10 mm. A perforated tray (6) is installed in the lower part of the chamber for the product to be put in for freezing. The tray is perforated because as a result of sublimation, the refrigerating agent settles at the bottom of the chamber. In the lower part of the chamber, there is a nozzle for receiving carbon dioxide gas (7) and feeding it to the compressor of the first stage. To reduce heat flows, thermal insulation (8) made of Penoplex polystyrene with a thickness of 40 mm is applied to the chamber.

In the next stage, a 3D model of the refrigeration unit was developed. Isometric projections of the 3D model are shown in Figures 1(c) and 1(d). Stainless steel was used as a material for the manufacture of nozzles and manifolds installed in the chamber to reduce the risk of material corrosion. The chamber must be sealed at a maximum pressure of 5 MPa. The installation should be as compact as possible, with the ability to be moved around production sites.

AutoCAD multifunctional software for creating 2D and 3D models was used in the design.

The requirement for the design of the refrigeration unit was to make it as compact as possible, for subsequent unhindered transportation inside industrial premises. This requirement is determined by the customer's technical specifications because technological lines are located in different rooms and their operating principle is cyclical. However, the location of the equipment should allow the operation of the refrigeration unit and ensure its safety by reducing the amount of refrigerant charged into the system, as well as increasing sealing, which was achieved by the compact arrangement of the refrigeration equipment on a welded frame.



Note: (1: first-stage compressor, 2: second-stage compressor, 3: third-stage compressor, 4: heat exchanger, 5: heat exchanger, 6: oil separator, 7: shell-and-tube condenser, 8 and 9: liquid separator, 10: linear receiver, 11: chamber, 12: liquid separator.
Source of the layout: [13].

Figure 1. a) Layout of a three-stage refrigeration unit running on carbon dioxide; b) Isometric projection of the refrigeration unit chamber; c) Isometric projection of a 3D model of the refrigeration unit (view 1); d) Isometric projection of a 3D model of the refrigeration unit (view 2)

Special attention was also paid when designing the pipelines of the system. The presence of a large number of turns leads to an increase in hydraulic losses. Therefore, their number was reduced as much as possible. Hydraulic losses are also affected by the length of the pipeline, which was assumed to be minimal. It is worth noting the location of the refrigerator. Placing the chamber on the upper part of the frame allowed us to reduce the overall dimensions of the unit [8, 14].

At the final stage of the design, complex automation of the system was carried out, which allows for increasing the level of safety, energy efficiency, and optimization, as well as reducing the participation of people in the maintenance of the unit.

The complex automation process included the following aspects: temperature control in the chamber, protection of compressors from low and high suction pressure, control of the level of the refrigerating agent in liquid separators, control of oil supply to compressors, as well as pressure and temperature control on all equipment of the refrigeration system. The elements included in complex automation are presented below.

1. TE temperature sensor. This temperature sensor is located in the refrigeration chamber. When the temperature in the chamber drops to the set value (-45°C), the sensor is triggered and sends a signal to the compressor panel. The signal starts the first-stage compressor and the refrigerant begins to be sucked out of the chamber;

1’, 5’, 9’. PSA low-pressure block of a two-block pressure switch. Located on the suction pipe. Protects the compressor from low suction pressure;

2, 6, 10. PSA high-pressure block of a two-block pressure switch. Located on the discharge pipeline. Protects the compressor from too high discharge pressure;

3, 7, 11. TI thermocouple. Located on the suction pipe. Indicates the suction refrigerant temperature. Sends a signal to the OVEN-PLK100 controller;

4, 8, 12. FSA flow meter Controls the flow of oil from the oil separator to the compressor;

5. PE pressure sensor. This pressure sensor is located on the suction pipe of the second-stage compressor. When the pressure in the pipeline rises to a preset value (2.57 MPa), the sensor is triggered and sends a signal to the compressor panel. The signal starts the second stage compressor and the refrigerant begins to be sucked out of the pipeline;

9’. PE pressure meter. This pressure sensor is located on the suction pipe of the third-stage compressor. When the pressure in the pipeline rises to a set value (4.28 MPa), the sensor is triggered and sends a signal to the compressor panel. The signal starts the third stage compressor and the refrigerant begins to be sucked out of the pipeline;

13-19. TI thermocouple. Located on the suction pipe. Indicates the suction refrigerant temperature. Sends a signal to the OVEN-PLK100 controller;

19’ OVEN-PLL100 controller. The controller receives the signal from thermocouples of the refrigeration unit;

20, 21. LE level sensor. Located on the liquid separator. When the liquid level in the liquid separator rises, a signal is sent to the solenoid valve. The solenoid valve shuts off the refrigerant supply to the liquid separator.

20’, 21’. SV solenoid valve. When the liquid level in the liquid separator rises, a signal is sent to the solenoid valve. The solenoid valve shuts off the refrigerant supply to the liquid separator.

22. TE temperature sensor. This temperature sensor is located in the refrigeration chamber. When the temperature in the chamber drops to the set value (-45°C), the sensor is triggered and sends a signal to the solenoid valve. The solenoid valve shuts off the flow of refrigerant into the chamber;

22’. SV solenoid valve. When the temperature in the chamber drops below the set value (-45°C), a signal is sent to the solenoid valve. The solenoid valve shuts off the flow of refrigerant into the chamber;

23. NS push-button starter. When the set temperature is reached (-45°C), the temperature sensor sends a signal to the compressor panel, the button starts the first-stage compressor;

24. NS push-button starter. When the set pressure (2.57 MPa) is reached, the pressure sensor sends a signal to the compressor panel, the button starts the second-stage compressor;

25. NS push-button starter. When the set pressure (4.28 MPa) is reached, the pressure sensor sends a signal to the compressor panel, the button starts the third-stage compressor;

26, 27. TE temperature sensor. Located at the refrigerant outlet from the heat exchanger. When the temperature drops below the set value (-15°C), a signal is sent to the thermostatic valve. The thermostatic valve, in turn, shuts off the cold-water supply to the heat exchanger;

26’, 27’. TDS thermostatic valve. Located on the cold-water pipeline. Shuts off the cold-water supply when the temperature of the refrigerant at the outlet of the heat exchanger drops below the set value (-15°C);

28-38. PI monometer. Device indicating pressure;

39. PC pressure regulator “towards itself”. Controls the pressure at the outlet of the refrigeration chamber. When the set value is exceeded (4.28 MPa), the valve closes;

40. PI pressure gauge. Device indicating pressure. Located on liquid separators;

41. TI thermocouple. Located on the suction pipe. Indicates the suction refrigerant temperature. Sends a signal to the OVEN-PLK100 controller.

Table 2 presents installation automation elements.

Table 2. Explication of refrigeration unit automation devices

Designation	Name	Quantity
1, 22	Temperature sensor NTC015HP00	1
1’, 2, 5’, 6, 9’, 10	Double block pressure switch PS2-47A	3
3, 3’,7, 7’, 11, 11’, 13-19, 41	Thermocouple TP-A-4001	13
4, 8, 12	Flow meter VS1340G21WO	3
5, 9	Pressure sensor PT5-150D	1
19’	Controller OVEN-PLK 100	1
20, 21	Level sensor HBLT-A1	2
20’, 21’, 22’	Solenoid valve SV1078/4	3
23, 24, 25	Push-type starter PNVS-10	3
26, 27	Temperature sensor EKS211	2
26’, 27’	Thermostatic valve TE5-55	2
28-38, 40	Pressure gauge TM 350 P	12
39	Pressure regulator “towards itself” CVP-HP	1

4. RESULTS AND DISCUSSION

Table 3 presents the comparative characteristics of carbon dioxide with the most common freon refrigerants [15].

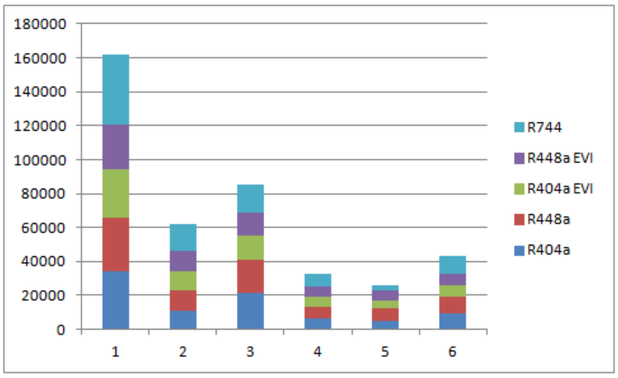
Table 3. Comparative characteristics of carbon dioxide with freon refrigerants

Refrigerant		COP	kWh/year (Fixed Condensation)	kWh/Year (Floating Condensation)	Indirect Impact on Global Warming, kg of CO_2	Impact on Global Warming at Full Leakage, kg of CO_2	Total Impact on Global Warming, kg of CO_2
R404A	MT	2.31	582,911	231,369	281,713	2,203,500	2,485,213
	LT	1.19	315,673	171,480			
R448A	MT	2.37	568,154	225,511	279,666	748,015	1,027,681
	LT	1.17	321,070	174,412			
R404A (LT EVI)	MT	2.07	650,495	258,194	270,872	1,792,500	2,063,372
	LT	1.58	237,754	129,153			
R448A (LT EVI)	MT	2.1	641,202	254,506	279,182	608,494	887,676
	LT	1.41	266,419	144,725			
R744 (transcritical flow)	MT	1.79	900,469	398,770	332,819	758	333,577
	LT	3.86	77,161	77,161			

Note: COP: coefficient of performance, MT: medium temperature, LT: low temperature

Table 3 shows that in terms of environmental safety, carbon dioxide is the most promising refrigerant. Despite the fact that CO_2 is a greenhouse gas (the greenhouse effect of CO_2 is taken as a unit of GWP), its use as a refrigerant instead of hydrofluorocarbons (HFCs) can significantly reduce both direct greenhouse emissions due to leakage (HFCs have a GWP a thousand times the GWP of CO_2) and indirect greenhouse emissions due to electricity generation (many CO_2 store refrigeration systems are more energy efficient than HFC systems of similar capacity).

Figure 2 shows comparative data on the capital costs of designing systems based on traditional refrigerants and carbon dioxide [16].



Note: 1: refrigerating machine, 2: condensers (gas coolers), 3: pipelines, 4: automation, 5: refrigerant, 6: installation), in rubles at the rate of $1 = 76 rubles

Figure 2. Comparative data on capital expenditures for the design of systems based on traditional refrigerants and carbon dioxide

Despite the positive data on the environmental side, the design of systems based on carbon dioxide is more expensive than the design of refrigerating machines running on most other refrigerants.

Analysis of the consumer refrigeration market shows that despite the high cost of production of refrigerating machines based on carbon dioxide, as well as due to the restrictions of the world environmental oversight organizations, the popularity of CO_2 as a refrigerant is increasing every year [17, 18].

The European and American markets for the production and consumption of refrigeration actively use carbon dioxide as an alternative to traditional refrigerating agents. The demand for CO_2 cooling systems based on transcritical cycles has been very significant in the retail sector and public catering [19, 20].

Due to the tightening of measures to control emissions of environmental pollutants into the atmosphere, carbon dioxide is actively attracting the attention of advanced industrial refrigeration enterprises in the world [16]. In particular, subcritical cascade refrigerating machines are being actively put into operation, the lower cooling circuit of which operates based on carbon dioxide.

In Russia, this field is just beginning to develop actively at the time of 2022. Despite this, there are many Russian companies offering products based on CO_2 in the market providing services for the design and development of refrigeration systems [21]. Thus, the pioneers in the direction of subcritical carbon dioxide systems in the RF are such trading giants as Lenta LLC and Zelgros LLC, and METRO LLC is actively introducing transcritical cooling systems running on carbon dioxide into its commercial refrigeration units [21]. However, all these units are airtight and have several disadvantages, such as high pressures in an airtight system, increased cost of equipment, the use of additional equipment in circuits, and a long duration of freezing, because there is no direct contact with the material [5]. The developed unit, which operates on the principle of direct contact of the refrigerating agent with the product, avoids the described disadvantages, and the recirculation system allows for avoiding leaks of CO_2 into the atmosphere.

5. CONCLUSION

As a result of the design, a schematic solution of a refrigeration unit for contact freezing with carbon dioxide recirculation has been developed. Based on the performed calculations, we made design decisions and selected modern refrigeration equipment with its complex automation.

The design of this refrigeration unit in a three-dimensional system made it possible to minimize the overall dimensions of the system by up to 30% due to the competent layout of refrigeration equipment through the use of 3D models of equipment, which made it possible to assemble components in real time and in the form of models.

The principle of recuperation implemented in the unit will reduce the consumption of the refrigerating agent by up to 80% in contrast to similar installations, but without recovery, and the principle of direct contact between carbon dioxide and the product will increase the freezing rate by 30% due to heat exchange intensification.

This study was limited to the use of R744 as a refrigerant. The use of R744 reduces the concentration of emissions of ozone-depleting refrigerants, having a beneficial effect on the current environmental situation. In further research, it is necessary to continue studying the use of various natural substances as refrigerants.

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