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ҚАЗАҚСТАН РЕСПУБЛИКАСЫ ПРЕЗИДЕНТІНІҢ ЖАНЫНДАҒЫ ҚАЗАҚСТАН РЕСПУБЛИКАСЫ ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫ

КАЗАХСКИЙ НАЦИОНАЛЬНЫЙ АГРАРНЫЙ ИССЛЕДОВАТЕЛЬСКИЙ УНИВЕРСИТЕТ
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VACUM FREEZE-DRYING SYSTEM WITH INVERTER COMPRESSOR

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Abstract. This study presents the development and experimental validation of an intelligent vacuum freeze-drying system operating from a single-phase 220 V power supply. The system was designed to improve the energy efficiency and operational stability of freeze-drying processes for small and medium-scale food production facilities under conditions of limited electrical infrastructure. The developed installation integrates an inverter compressor and a sequential load control algorithm for energy-intensive components, including the refrigeration system, vacuum pump, and heating system. Experimental investigations were carried out during the freeze-drying of goat milk with a product load of up to 45–50 kg. Temperature, pressure, mass-transfer, and energy-consumption parameters were monitored throughout the drying cycle. The obtained results demonstrated stable maintenance of the vacuum regime within 45–55 Pa and condenser temperature within -46 to-48 °C during the primary sublimation stage. The implemented sequential control algorithm limited peak electrical power consumption to 6.5 kW and ensured stable operation from a standard single-phase 220 V electrical network. Experimental drying of goat milk resulted in residual moisture content of 1.8–4.2 % and moisture removal efficiency exceeding 95 %. Comparative analysis confirmed lower installed power and reduced energy consumption compared with conventional three-phase freeze-drying systems. The obtained results confirm the practical feasibility of applying the developed intelligent vacuum freeze-drying system in farms and small food processing enterprises in Kazakhstan. Vacuum freeze-drying system.

Keywords: vacuum freeze-drying, inverter compressor, intelligent control system, sequential load control, energy efficiency, goat milk, lyophilization, single-phase 220 V power supply, vacuum chamber

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ИНВЕРТОРЛЫҚ КОМПРЕССОРЫ БАР ВАКУУМДЫҚ СУБЛИМАЦИЯЛЫҚ КЕПТІРУ ЖҮЙЕСІ

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Аннотация. Бұл жұмыста бір фазалы 220 В электр қоректендіру желісінен жұмыс істейтін интеллектуалды вакуумдық сублимациялық кептіру жүйесінің әзірленуі және эксперименттік тексерілуі ұсынылған. Жүйе электрлік инфрақұрылымы шектеулі жағдайларда шағын және орта тағам өндірісі кәсіпорындары үшін сублимациялық кептіру үдерістерінің энергия тиімділігі мен пайдалану тұрақтылығын арттыру мақсатында жасалған. Әзірленген қондырғы құрамына инверторлық компрессор жане энергияны көп тұтынатын компоненттерге, соның ішінде тоңазыту жүйесіне, вакуумдық насосқа және қыздыру жүйесіне арналған жүктемені тізбектеп басқару алгоритмі енгізілген. Эксперименттік зерттеулер 45–50 кг дейін өнім жүктелген жағдайда ешкі сүтін сублимациялық, кептіру барысында жүргізілді. Кептіру циклі бойы температура, қысым, массаалмасу және энергия тұтыну параметрлері бақыланды. Алынған нәтижелер негізгі сублимация кезеңінде вакуумдық режимнің 45–55 Па ара-лығында, ал конденсатор температурасының 46-дан 48°С аралығында тұрақты сақталғанын көрсетті. Жүзеге асырылған жүктемені тізбектеп басқару алгоритмі электр қуатының шекті тұтынуын 6,5 кВт деңгейінде шектеп, стандартты бір фазалы 220 В электр желісінен тұрақты жұмыс істеуді қамтама-сыз етті. Ешкі сүтін эксперименттік кептіру нәтижесінде өнімнің қалдық ылғалдылығы 1,8 4,2 % ара-лығында болып, ылғалды жою тиімділігі 95 %-дан жоғары болды. Салыстырмалы талдау дәстүрлі үш фазалы сублимациялық кептіру жүйелерімен салыстырғанда орнатылған қуаттың және энергия тұты-нудың төмендегенін растады. Алынған нәтижелер әзірленген интеллектуалды вакуумдық сублимаци-ялық кептіру жүйесін Қазақстандағы фермерлік шаруашылықтар мен шағын тағам өнеркәсібі кәсіпо-рындарында қолданудың практикалық мүмкіндігін дәлелдейді.

Түйін сөздер: вакуумдық сублимациялық кептіру, инверторлық компрессор, интеллектуалды басқару жүйесі, жүктемені тізбектеп басқару, энергия тиімділігі, ешкі сүті, лиофилизация, бір фазалы 220 В қоректендіру жүйесі, вакуумдық камера

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ВАКУУМНАЯ СУБЛИМАЦИОННАЯ СУШИЛЬНАЯ СИСТЕМА С ИНВЕРТОРНЫМ КОМПРЕССОРОМ

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Аннотация. В данной работе представлены разработка и экспериментальная проверка интеллектуальной вакуумной сублимационной сушильной системы, работающей от однофазной сети питания 220 В. Система разработана с целью повышения энергоэффективности и эксплуатационной устойчивости процессов сублимационной сушки для малых и средних предприятий пищевой промышленности в условиях ограниченной электрической инфраструктуры. Разработанная установка включает инверторный компрессор и алгоритм последовательного управления нагрузкой для энергоемких компонентов, включая холодильную систему, вакуумный насос и систему нагрева. Экспериментальные исследования проводились в процессе сублимационной сушки козьего молока при загрузке продукта до 45-50 кг. В течение всего цикла сушки контролировались параметры температуры, давления, массопереноса и энергопотребления. Полученные результаты показали стабильное поддержание вакуумного режима в пределах 45–55 Па и температуры конденсатора в диапазоне от 46 до 48 °C на основной стадии сублимации. Реализованный алгоритм последовательного управления ограничивал пиковое потребление электрической мощности до 6,5 кВт и обеспечивал стабильную работу от стандартной однофазной электрической сети 220 В. Экспериментальная сушка козьего молока обеспечила остаточную влажность продукта в пределах 1,8–4,2 % и эффективность удаления влаги свыше 95 %. Сравнительный анализ подтвердил снижение установленной мощности и уменьшение энергопотребления по сравнению с традиционными трёхфазными системами сублимационной сушки. Полученные результаты подтверждают практическую возможность применения разработанной интеллектуальной вакуумной сублимационной сушильной системы в фермерских хозяйствах и на малых предприятиях пищевой промышленности Казахстана.

Ключевые слова: вакуумная сублимационная сушка, инверторный компрессор, интеллектуальная система управления, последовательное управление нагрузкой, энергоэффективность, козье молоко, лиофилизация, однофазное питание 220 В, вакуумная камера

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Introduction.

At present, one of the most effective technologies for dehydrating food and biological products is vacuum freeze-drying, which ensures the preservation of the original structure, organoleptic properties, and biological value of the product. This technology is in high demand due to its high efficiency in drying milk, meat, berries, fruits, medicinal plant materials, and biological substances [Ruiz-Rodriguez et al., 2008].

In the Republic of Kazakhstan, the relevance of lyophilization is increasing due to the development of the agro-industrial complex, the need for deep processing of agricultural raw materials, and requirements for extending product shelf life while maintaining export potential. In recent years, the agro-industrial sector has been gradually expanding, which has created a growing demand for low-power and energy-efficient freeze-drying systems primarily intended for small farms and processing enterprises.

In addition, many industrial freeze-drying systems require a three-phase 380 V power supply, which is economically inefficient for small and medium-sized enterprises and rural areas. Under traditional control systems, the simultaneous operation of energy-intensive components (compressor, vacuum pump, and tray heaters) results in peak electrical loads, increasing the risk of emergency shutdowns when operating from a single-phase power supply. Currently, the main direction of freeze-drying system development is focused on intelligent and energy-saving solutions. To reduce starting currents in the refrigeration circuit, an inverter compressor can be used, allowing smooth regulation of operating modes. When such compressors are applied, electrical load control can be implemented in a sequential mode, where individual system components are activated and regulated step by step while considering power-consumption limitations.

In the conditions of Kazakhstan, the implementation of these solutions creates opportunities for the development of freeze-drying systems capable of operating efficiently from a standard single-phase 220 V power supply. This, in turn, leads to an increased demand for such installations.

Literature review and problem statement

A number of studies have shown that it is one of the most effective methods for dehydrating food and biological products in terms of preserving their physicochemical, structural, and biological properties. Many researchers report that freeze-drying results in lower losses of vitamins, proteins, and bioactive components compared with spray drying, while also ensuring high rehydration capacity of the final product. Studies confirm that the application of lyophilization significantly reduces the loss of vitamins, proteins, and bioactive compounds compared with convective and spray drying methods and provides high reconstitution quality of the dried product [Ruiz-Rodriguez et al., 2008; Ciurzyńska et al., 2011; Chen et al., 2024; Lozano et al., 2014: 703–707; Buana et al., 2025: 106930; Ben et al., 2025: e70163; Ratti, 2001].

The design of industrial freeze-drying systems is comprehensively examined, including their cooling systems and tray-heating systems. It is noted that maintaining temperature-vacuum regimes requires the use of high-power compressors and pumps, leading to increased energy consumption and the need for a three-phase power supply [Ben et al., 2025: e70163; Ratti, 2001; Chupawa et al., 2021: 1738]. However, issues related to adapting vacuum freeze-drying systems to conditions of limited electrical power and single-phase 220 V supply remain unresolved. Most existing technical solutions are oriented toward large industrial enterprises, whereas installations of such capacity are economically impractical for small and medium-sized production facilities and farms. The main reasons include compressor equipment with high starting currents and systems maintaining vacuum and temperature regimes operating simultaneously. High-power installations with this type of control operate exclusively from a three-phase electrical network, whereas single-phase systems are more appropriate for small farms and autonomous facilities [Chupawa et al., 2021: 1738; Fang et al., 2026: 131545; Jameel et al., et al., 2021; Nikiforidis et al., 2019].

Several studies propose the use of inverter compressors in refrigeration systems, which reduces starting currents, enables smooth regulation of cooling capacity, and improves energy efficiency. It has been shown that inverter control contributes to more accurate temperature regulation and reduced specific energy consumption. Another possible approach to overcoming these difficulties is the application of intelligent control systems with sequential activation and regulation of electrical loads [Bano et al., 2020: 5056–5071; Abascal et al., 2005; Liu et al., 2024: 884; Lazarin et al., 2023: 565–575]. This approach is considered in several studies, where the possibility of redistributing load over time and reducing maximum power consumption is demonstrated. However, in existing research, such solutions are typically considered fragmentarily and are not adapted to the specific features of vacuum freeze-drying systems or to operation under a 220 V power supply. Furthermore, the available literature provides limited discussion on the integrated implementation of inverter compressors and sequential load-control algorithms within a unified intelligent control system for freeze-drying installations. A systematic analysis of the influence of these solutions on process stability, energy efficiency, and operational reliability is still lacking [Ruiz-Rodriguez et al., 2008; Li et al., 2023: 01004; Ilić et al., 2005: 1920–1940; Wang et al., 2023; Nst et al., 2025: 178–183].

These considerations indicate the relevance of research focused on the development and analysis of an intelligent vacuum freeze-drying system with an inverter compressor and sequential electrical load control capable of efficient operation from a single-phase 220 V power supply without compromising freeze-drying quality [Stetzer et al., 2008: 64–74; Oztuna Taner, 2024: 38573–38584; Sapakov et al., 2024: 414–422, Liliana et al., 2015: 442–450].

The objective of this study is to develop, experimentally validate, and scientifically substantiate an intelligent vacuum freeze-drying system with an inverter compressor and a sequential load-control algorithm that ensures energy-efficient freeze-drying of food products when powered by a single-phase 220 V electrical network and operating with an increased product load of up to 45–50 kg [Stetzer et al., 2008: 64–74; Alfat et al., 2017; Sun Z. et al., 2025: e70238; Morikawa et al., 2017: 831–838; Prosapio et al., 2017: 1171–1179; Zhang et al., 2022: 1267–127; Bayana et al., 2024: 5000–5022].

To achieve this objective, the following tasks are addressed in this work: development of a functional and physical model of a compact freeze-drying system with an inverter compressor and an intelligent control system; implementation of a sequential control algorithm for energy-intensive units (refrigeration system, vacuum pump, and heating system) to limit peak electrical loads under single-phase 220 V power supply, experimental investigation of the influence of increased product loading on the temperature and vacuum operating modes of the cooling system and condenser; determination of the main thermal, vacuum, mass-transfer, and energy parameters of the vacuum freeze-drying process under different operating modes; evaluation of the efficiency of vacuum freeze-drying of goat milk based on moisture removal depth and the dynamics of temperature, pressure, and moisture-content changes; comparative analysis of the energy and operational characteristics of the developed system with traditional three-phase vacuum freeze-drying systems; justification of stable and energy-efficient operation of the intelligent vacuum freeze-drying system under conditions of limited electrical infrastructure and single-phase power supply [Zhang et al., 2023: 2679-2687; Wang et al., 2026: 108279; Jameel et al., et al., 2021; Abascal et al., 2005].

The scientific novelty of this study lies in the development of an intelligent vacuum freeze-drying system with an inverter compressor and a sequential load-control algorithm, capable of stable operation from a standard single-phase 220 V electrical network with a product load of up to 45–50 kg. Unlike conventional freeze-drying systems requiring a three-phase power supply, the proposed system implements sequential control of the compressor, vacuum pump, and heating elements, which limits peak power consumption to 6.5 kW while maintaining stable technological parameters of the drying process. The scientific contribution of the study consists of the development and experimental validation of a sequential load-control algorithm integrated with an inverter compressor, enabling stable operation of a 45–50 kg vacuum freeze-drying system from a single-phase 220 V power supply.

Materials and Methods.

In the laboratory of the Department of Energy and Electrical Engineering of the Kazakh National Agrarian Research University, a simplified physical model of a compact vacuum freeze-drying system was installed, as shown in Figure 1.

Description of the Experimental Setup

The experimental vacuum freeze-drying system consisted of a vacuum chamber, a refrigeration system with an inverter compressor, a condenser, a vacuum pump, electric heating elements, a control valve, temperature and pressure sensors, and a Siemens S7–1200 programmable logic controller (PLC), as shown in Figure 1. The product was placed on trays equipped with electric heating elements installed beneath them.

The refrigeration system employed an inverter-driven compressor providing smooth cooling-capacity regulation, reduced starting current, and improved energy efficiency.

The condenser temperature was maintained within the range from –46 to –48 °C, while the vacuum pump generated and maintained the operating pressure in the range of 45–55 Pa. Moisture removed from the product during sublimation was deposited on the cooled condenser surface in the form of ice. The pressure inside the chamber was measured using a vacuum sensor, and all measured signals were transmitted to the PLC-based control system. A control valve was used to regulate and release the vacuum inside the chamber.

The Siemens S7–1200 PLC monitored temperature and pressure parameters and coordinated the operation of the inverter compressor, vacuum pump, heating elements, and control valve according to the developed sequential load-control algorithm. This control strategy enabled stable operation of the freeze-drying system from a standard single-phase 220 V power supply while limiting peak power consumption. The structural configuration of the experimental setup is presented in Figure 1, whereas the flowchart of the sequential load-control algorithm is shown in Figure 4.

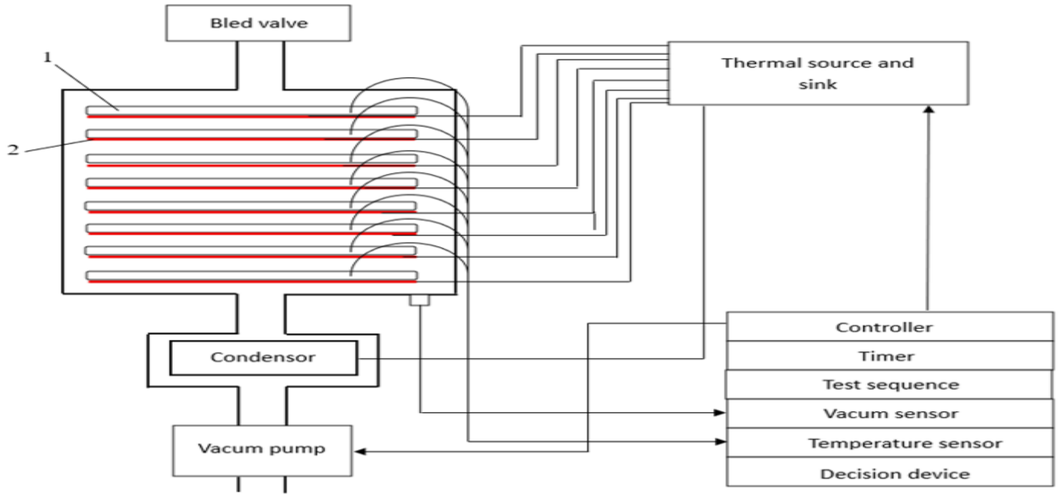

Fig. 1. Functional diagram of the vacuum freeze-drying system with tray-heating control, condenser cooling, and vacuum supply, where: 1- trays for product placement; 2-electric heating elements of the trays in the cooling system and condenser of the freeze-drying unit

The freeze-drying process included the following stages: product preparation and loading into the vacuum chamber (up to 45–50 kg), preliminary cooling and freezing, vacuum generation, primary sublimation drying, sequential control of electrical loads, secondary drying for the removal of residual moisture, and completion of the drying process. The mass of the product was measured at different stages of the process using laboratory scales, where m_1 is the product mass before freeze-drying (kg), and m_2 is the product mass after completion of the primary sublimation stage (kg). These values were used to determine the amount of removed moisture and to evaluate the performance of the freeze-drying system under increased product loading conditions.

Freeze-drying under increased product load in laboratory conditions

Considering the objective of the research task, the development, design justification, and experimental validation of a freeze-drying unit with a capacity of 45–50 kg powered by a single-phase electrical network, the experiment was aimed at evaluating the operational performance of the unit and optimizing the freeze-drying process under increased product load. Based on the above-mentioned model of the freeze-drying unit, experimental measurements were carried out at different product load levels according to the following variables: p_1-pressure in the vacuum chamber at the initial stage of sublimation, Pa; p_2-pressure in the vacuum chamber during the period of intensive moisture release from the product, Pa; t_p - change in product temperature during sublimation, °C; t_c - temperature of the inner surface of the condenser, °C; $\dot{m}_w$ - mass flow rate of sublimated moisture entering the condenser at different product load levels, kg/s; τ_s - duration of the sublimation drying process, h; N-energy consumption of the unit under sequential control, kWh.

Using the freeze-drying unit, 14 measurements of goat milk samples were carried out. Measurements No. 1–9 were conducted in February 2022, while measurements No. 10–14 were performed in April 2022. The results of the experiments conducted under different operating modes are presented in Table 1. During the measurement process, the moisture content of the goat milk samples was determined: w_{c1}, initial moisture content of the product before the start of freeze-drying; w_{c_2}- moisture content after completion of the primary sublimation stage and removal of the sample from the vacuum chamber.

The moisture content was determined using a Class I laboratory hygrometer. Prior to the experiment, a metrological verification of the measurement accuracy of the instruments was performed. During measurements No. 9–14, the moisture content of the goat milk sample reached 6.7 %. The measurement conditions and the parameters used are presented in Table 2. The obtained results were used to analyze the performance of the freeze-drying unit.

Table 1 – Values of Measured Variables During Freeze-Drying of Goat Milk

p_1 - product temperature in the vacuum chamber, °C; t_{p1max} - maximum milk temperature, °C; $t_{p2, max}$ - change in product temperature when the heating system is switched on, °C; $t_{p,avg}$ - average milk temperature during the freeze-drying process, °C; p_{avg} - average pressure in the vacuum chamber during the freeze-drying process, Pa; t_s - temperature of the heated shelf in the vacuum chamber, °C; τ_2 - duration of the primary sublimation stage, h; m_{L1} - mass of the loaded product at the beginning of sublimation, kg; m_{L2} - mass of the product after completion of sublimation, kg.

Measurement No.	p_1, Pa	t_{p1},max, °C	t_{p2},max, °C	p_{max}, Pa	t_p,avg, °C	$(t_{p2}-t_{p1})$, min	τ_2, h:min	mL₁, g	mL₂, g
1	100.76	55.2	5.82	45.6	38.8	1.9	1:06	1300.00	1293.78
2	102.77	50.9	5.91	43.9	38.9	2.1	0:45	1300.00	1295.00
3	102.45	52.7	6.62	44.9	39.1	2.3	0:54	1300.00	1294.80
4	101.95	60.3	9.19	52.4	46.9	1.7	0:37	1300.00	1292.82
5	101.66	60.6	9.81	53.8	48.4	0.6	0:34	1300.00	1292.00
6	101.28	59.8	9.51	53.8	48.8	3.0	0:33	1300.00	1291.49
7	102.06	61.6	9.35	61.6	62.7	17.6	0:57	1300.00	1294.20
8	101.95	62.6	9.26	61.5	60.2	15.6	0:56	1300.00	1290.36
9 (2 cycles)	101.93	60.5	8.66	54.1	48.6	4.6	1:26	1300.00	1282.93
9 (1 cycle)	101.93	60.5	9.02	54.0	48.7	3.6	0:40	1300.00	1289.80
9 (2 cycles)	101.69	60.4	8.31	54.1	48.6	5.5	0:46	1289.80	1282.86
10	100.74	60.0	9.74	54.2	48.7	2.6	0:48	1300.00	1295.00
11	99.90	61.4	9.70	55.2	48.5	2.2	1:29	1300.00	1297.11
12	102.08	60.0	8.41	59.5	59.5	16.9	0:28	1300.00	1296.86
13	101.95	60.5	9.42	60.7	59.6	14.2	0:42	1300.00	1295.80
14	100.00	60.1	8.73	61.0	62.8	18.2	0:58	1300.00	1295.90

Table 2 – Laboratory Conditions for Determining the Moisture Content of Goat Milk

Parameter	Value
Pre-drying temperature, °C	60±1
Pre-drying time, min	360
Sample mass before drying, g	10
Physical state of the product	Liquid (goat milk)
Main (reference) drying temperature, ^{0}C	130±1
Main drying time, min	240
Sample mass after pre-drying, g	5
Sample condition during main drying	Dried residue (ground)

The initial moisture content wel of representative goat milk samples under two experimental conditions was determined using the gravimetric method and had the values presented in Table 3: w_{c1}=10.487 % for measurements performed in February 2022; w_{c1}=8.858 % for measurements performed in April 2022. The initial moisture content was determined using representative milk samples with masses of g (February 2022) and =9.996 g (April 2022).

The mass of the goat milk sample was defined as follows: - at the beginning of the experiment, g; - after completion of vacuum freeze-drying (lyophilization), g. Based on the initial moisture content we, the dry matter mass ma, and the moisture content after drying were calculated. The obtained values were used to evaluate the efficiency of the vacuum freeze-drying process.

Table 3 – Results of determining the dry matter mass and moisture content we in the milk sample

Period of goat milk moisture content measurement	February 2024	April 2024
Mass of goat milk sample, m_l, g	10.000	9.996
Mass of the sample after preliminary freezing and vacuuming, g	9.800	9,866
Mass of the sample before primary freeze-drying, g	5.000	5.002
Mass of the sample after primary freeze-drying, g	4.567	4.619
Dry matter mass in the sample, ma, g	8.951	9.111
Moisture content of the goat milk sample, w_c, %	10.487	8.858

The mass of dry matter ma in goat milk is determined by the following equation:

$$m_d = m_{L1}\left(1 - \frac{w_{c1}}{100}\right), \text{г} \tag{1}$$

where: m_{L1} mass of the goat milk sample at the initial stage of the experiment, g; w_{c1} - initial moisture content of goat milk, %.

The process of vacuum freeze-drying of goat milk is shown in Figure 2. Figure 2a presents the placement of trays with product samples inside the vacuum chamber of the freeze-drying unit. Figure 2b shows the preparation and placement of frozen goat milk samples on trays before sublimation. Figure 3c illustrates the deposition and accumulation of ice on the condenser surface during the freeze-drying process. Figure 2d shows the freeze-dried goat milk obtained after the process.

The relative moisture content of the goat milk sample (mass fraction of moisture) is defined as the ratio of the moisture mass m_{wi} to the sample mass m_{L1} and is calculated using the following expression:

$$w_{ci} = 100 \cdot \frac{m_{wi}}{m_{L1}} = 100 \cdot \frac{m_{L1} - m_d}{m_{L1}} = 100 \cdot \left(1 - \frac{m_d}{m_{L1}}\right), \% \quad (2)$$

where: m_{wi} - mass of moisture contained in the goat milk sample, g.

$\Delta w_c = w_{c1} - w_{c2}$ (%)

Fig.2. Vacuum freeze-drying process of goat milk

The moisture content of the goat milk sample after completion of the primary sublimation stage, w_{c2}, is determined by the gravimetric method based on the calculated dry matter mass m_d and the experimentally measured sample masses m_{L2} and m_{L3}, respectively, in accordance with the data presented in Table 1. Measurements of milk samples performed during freeze-drying under specified operating conditions can be compared using the following parameters.

The difference in moisture content Δw_c of the milk sample between the initial moisture content w_{c1} at the beginning of the experiment and the moisture content w_{c2} after completion of the secondary drying stage, which ensures the removal of residual bound moisture, is determined by the following expression:

$$\Delta w_c = w_{c1} - w_{c2} \ (\%) \quad (3)$$

The relative moisture content difference $\Delta w_{c,rel}$ of the goat milk sample is defined as the ratio of the moisture content difference Δw_c to the initial moisture content of the product w_{c1} and is calculated using the following formula:

$$\Delta w_{c,rel} = 100 \cdot \frac{w_{c1} - w_{c2}}{w_{c1}} \ (\%) \quad (4)$$

These indicators make it possible to quantitatively evaluate the efficiency of the vacuum freeze-drying process. Leaks in the vacuum system lead to an increase in chamber pressure pi. The pressure during the heating and sublimation stages was characterized by its average value pi,avg. It was recorded that the maximum product temperature under all operating modes reached tp1,max =60±3°C.

During the heating stage, the chamber pressure pl remained within the range of 99.90–102.77 Pa. At the beginning of the sublimation stage, the temperature tp1, max coincided with $t_{p2,max}$. During freeze-drying of milk, according to measurements No. 1-3, the average chamber pressure pavg was in the range of 43.9–45.6

Pa. During these measurements, the maximum product temperature tp1, max increased to 50.9–55.2 °C.

Measurements No. 4-14 were carried out at an average chamber pressure pavg in the range of 52.4-61.6 Pa, while the maximum product temperature at the end of the heating stage was within 59.8-62.6 °C. During the freeze-drying process, heat was removed from the dry portion of the product, resulting in a decrease in product temperature from t_{p2} to $t_{p2,min}$.

The decrease in temperature t_{p2} was determined by the magnitude of the thermal power supplied by the heating system. The value of the temperature $t_{p1, max}$ during the heating stage was selected so that, at the end of the sublimation process, the minimum product temperature $t_{p2, min}$ remained higher than the saturation temperature of water vapor $t_s(p_2)$ at the corresponding pressure p_2. In experiments No. 1–6 and no. 9-11, a reduction in the thermal power supplied by the heating system was carried out. Sublimation was completed when the minimum temperature difference $(t_{p2,min}-t_s)_{min}$ reached a range of 0.6–5.5 °C. In experiments No. 7, No. 8, and No. 12–14, the thermal power supplied by the heating system was entirely consumed for the sublimation of moisture removed from the product. The temperature difference during sublimation drying between the initial value $t_{p1, max}$, and the final value $t_{p2, min}$ ranged from -2.7 to 2.4 °C. Upon completion of the sublimation process, the value $(t_{p2,m} - t)_{in}$ was 14.2–18.2 °C. After completion of the sublimation process, the product was removed from the vacuum chamber and weighed. During sublimation, the product mass decreased to the value m_{l2}. At the final drying stage, residual moisture was removed from the milk by additional heat supply, after which its final mass m_{L3} was determined.

Sequential Load-Control Algorithm of the Intelligent Vacuum Freeze-Drying System

To ensure stable operation of the developed vacuum freeze-drying unit operating from a single-phase power supply, a sequential load-control algorithm was developed. The proposed control strategy coordinates the operation of the compressor, vacuum pump, and heating elements in order to limit peak power consumption while maintaining the required technological parameters of the freeze-drying process. The control sequence begins with loading the product into the vacuum chamber, followed by PLC initialization and verification of all temperature, pressure, and system-status sensors. If a fault is detected during the diagnostic procedure, the system enters an emergency shutdown mode, activates an alarm signal, and initiates troubleshooting procedures before returning to system verification. After successful diagnostics, the product undergoes preliminary cooling and freezing. Subsequently, a vacuum is generated inside the drying chamber. The chamber pressure is continuously monitored, and the process proceeds only after the operating pressure range of 45–55 Pa has been achieved. If the required pressure level is not reached, vacuum generation and leak monitoring continue until stable operating conditions are established. Once the target pressure has been achieved, the major electrical loads are activated sequentially in the following order: compressor, vacuum pump, and heating elements. This operating strategy reduces peak electrical demand, prevents excessive loading of the single-phase power supply, and improves the overall energy efficiency of the freeze-drying system.

The primary sublimation drying stage is then initiated. During operation, the control system continuously monitors instantaneous power consumption and residual moisture content. If the instantaneous power consumption exceeds 6.5 kW, the control algorithm adjusts the load activation sequence and limits power demand to maintain stable operation. Similarly, if the residual moisture content remains above 6.7 %, the system continues the primary sublimation stage until the target moisture level is achieved. After reaching the required residual moisture content, the process proceeds to the secondary drying stage, where bound moisture is removed from the product. The drying cycle is completed by pressure equalization inside the chamber and unloading of the dried product. The flowchart of the proposed sequential load-control algorithm is presented in Figure 4. The algorithm ensures stable operation of the vacuum freeze-drying unit while limiting peak power consumption t kW and maintaining the required product moisture content throughout the drying process.

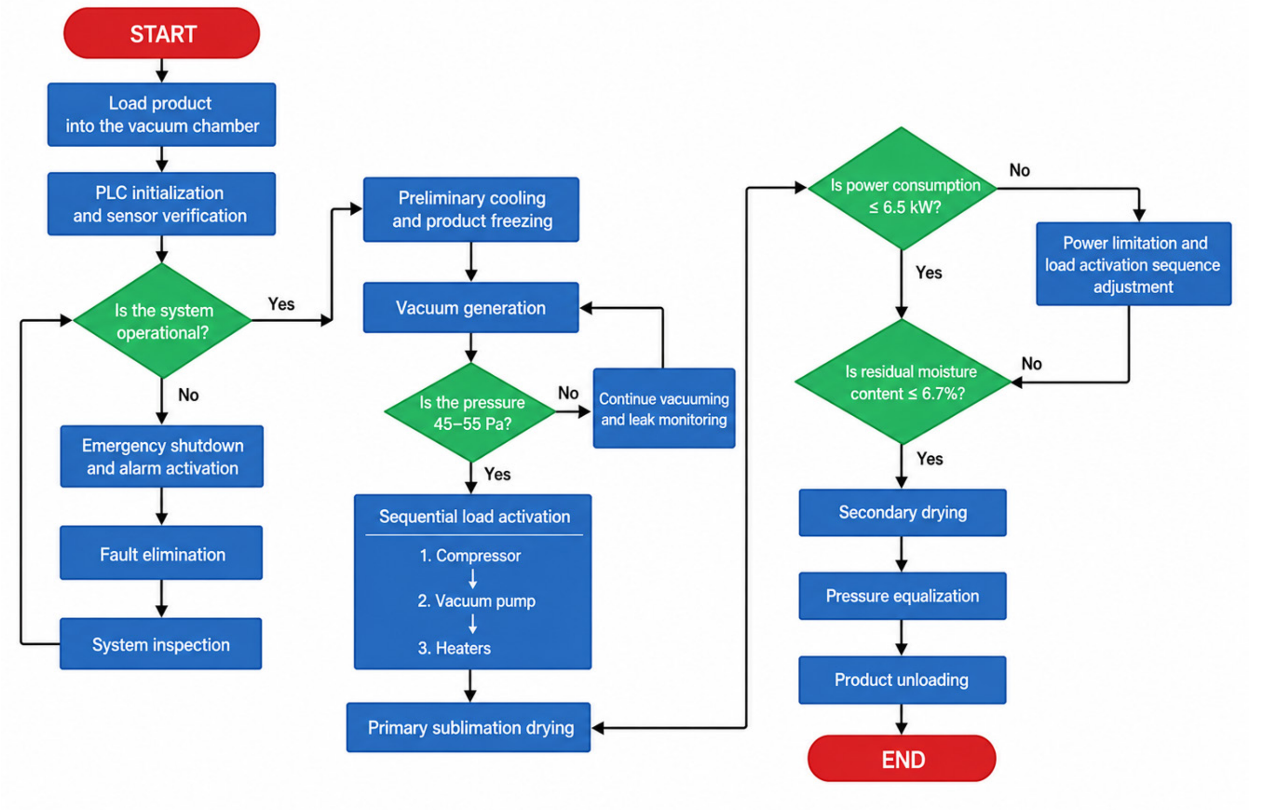

Fig.3. Flowchart of the Sequential Load-Control Algorithm for the Intelligent Vacuum Freeze-Drying System

Results.

All experimental studies were carried out with the same initial sample mass m_{l1}=100 g. Based on Equations (1-4), the dry matter mass m_d was determined. On this basis, the relative moisture content difference $\Delta w_{c,rel}$ was calculated. The values of moisture content w_{c1}, w_{c2}, w_{c3}, as well as the absolute moisture content difference $\Delta w_c = w_{c1} - w_{c3}$, are summarized and presented in Table 4.

Table 4 – Results of the calculation of the moisture parameters of goat milk samples

Measurement No.	mL_1, g	w_{c1}, %	m_d, g	w_{c2}, %	w_{c3}, %	Δw_c, %	Δw_{crel}, %
1	100.0	87.0	13.0	12.0	4.0	75.0	95.4
2	100.0	86.5	13.5	11.5	3.8	75.0	95.6
3	100.0	87.2	12.8	12.3	4.2	74.9	95.2
4	100.0	86.8	13.2	11.8	4.0	75.0	95.4
5	100.0	87.0	13.0	12.1	4.1	74.9	95.3

The results presented in the table indicate high drying efficiency

Change in Product Temperature Over Time During Vacuum Freeze-Drying

Based on the data presented in Table 1, the change in product temperature over time is shown in Diagram 5. The diagram presents three main temperature dependencies: t_p product temperature in the vacuum chamber, °C; t_h - temperature of the heating elements, °C; t_c - temperature of the inner surface of the condenser, °C. In the time interval of 0–1.5 hours, the product undergoes freezing. During this period, the product temperature decreases and moisture transitions into a solid state. In the interval of 1.5–3.0 hours, deep freezing is carried out. The product temperature decreases to -30 °C. The main sublimation process occurs within the interval of 3.0–6.0 hours.

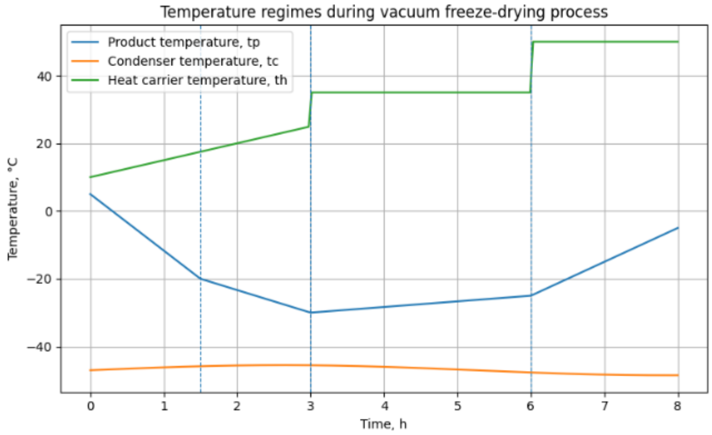

Fig. 5. Change in Product Temperature Over Time During Vacuum Freeze-Drying

The temperature of the heat carrier is approximately 35 °C, while the temperature of the condenser surface is -46...-48 °C. After 6.0 hours, the secondary drying stage begins. The temperature of the heat carrier increases to 50 °C. The temperature diagram demonstrates the correctness of the sublimation drying process and the stable operation of the unit powered by a single-phase 220 V electrical supply.

Influence of condenser temperature on sublimation intensity during freeze-drying

As shown by the temperature variation in the condenser, during the sublimation process within the interval of approximately 1.5–5.5 hours, the condenser temperature remained within the range of -46... -48 °C, indicating stable operation of the inverter compressor (Figure 6).

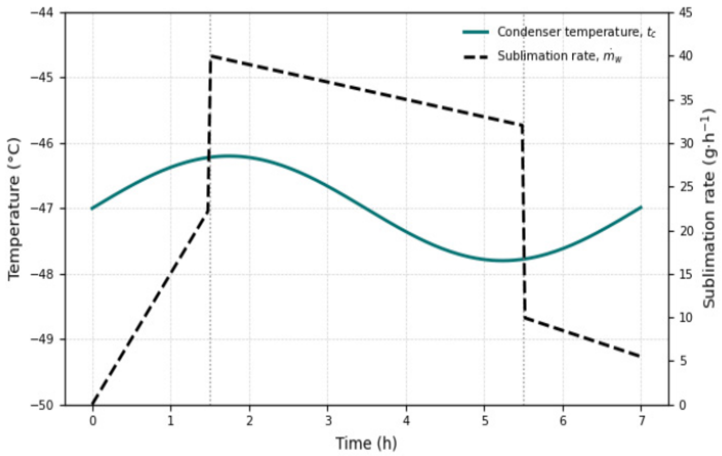

Fig.6. Dependence of condenser temperature and sublimation intensity on time during vacuum freeze-drying

Change in Pressure in the Vacuum Chamber

During the interval of 0-1.5 hours, the freezing process was carried out, and the pressure in the chamber remained at the atmospheric level (Figure 7).

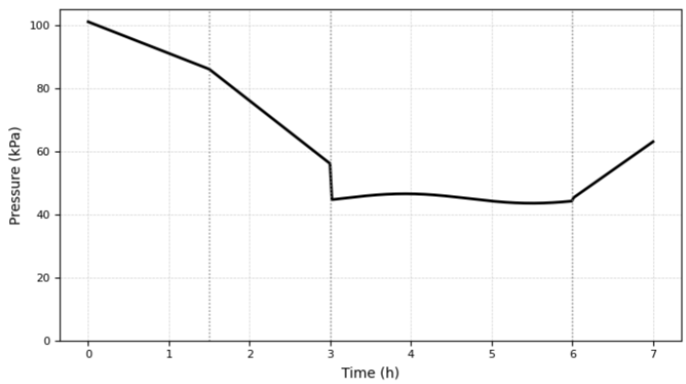

Fig.7. Change in Pressure in the Vacuum Chamber

In the interval of 1.5–3.0 hours, the vacuum mode was established. During the interval of 3.0–6.0 hours, the main stage of sublimation took place, while the pressure stabilized at approximately 45–50 Pa. After 6.0 hours, the pressure in the chamber gradually increased to the atmospheric level, indicating the correct completion of the technological cycle.

Relationship between pressure and product temperature

The relationship between pressure and product temperature is shown in Figure 7. As the product temperature varied within the range of -35...-20 °C, the pressure in the vacuum chamber was maintained at 45–55 Pa. The correspondence between pressure and temperature indicates the correct selection of vacuum regime parameters and thermal control.

The presented diagram reflects the physical relationship between the pressure in the vacuum chamber and the product temperature. The obtained relationship can be used to optimize freeze-drying operating conditions.

Change in product mass over time

Figure 8 shows three stages of freeze-drying: pre-cooling (0–1.5 h), primary sublimation (1.5–5.5 h), and secondary drying (after 5.5 h). The greatest reduction in product mass is observed during the primary sublimation stage, whereas during the secondary drying stage, the change in product mass slows down.

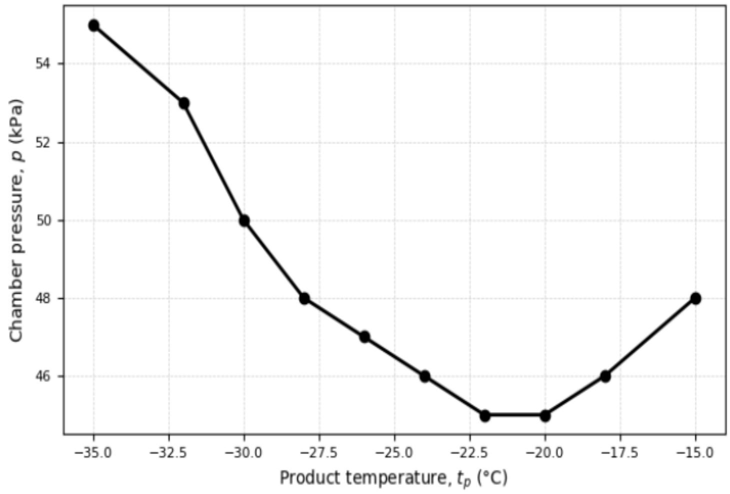

Fig. 8. Relationship Between Pressure in the Vacuum Chamber and Product Temperature During Vacuum Freeze-Drying

Change in product mass over time

Figure 9 shows three stages of freeze-drying: pre-cooling (0–1.5 h), primary sublimation (1.5–5.5 h), and secondary drying (after 5.5 h). The greatest reduction in product mass is observed during the primary sublimation stage, whereas during the secondary drying stage, the change in product mass slows down.

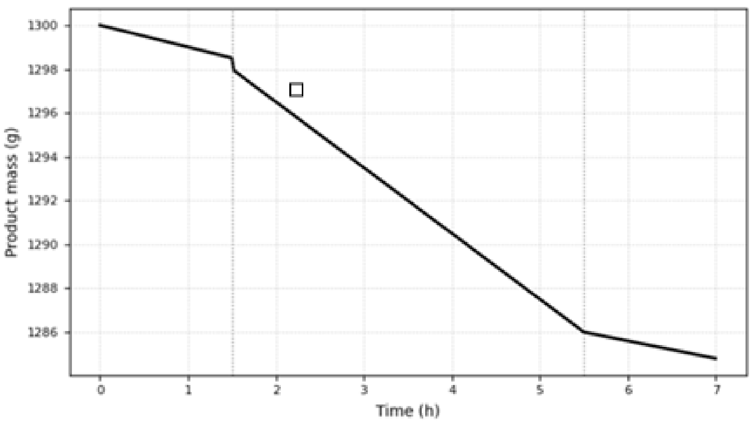

Fig.9. Change in Product Mass Over Time (Product Mass vs Time)

The obtained relationship describing the change in product mass over time confirms the correctness of the selected operating modes of vacuum freeze-drying.

Change in product moisture content

The diagram presented in Figure 9 shows the variation of the product moisture content during the process. The diagram indicates that at the initial stage (0–1.5 h), preliminary cooling takes place, while the moisture content changes only slightly from approximately 10.5 % to about 10.2 %, since the moisture remains in a solid state.

In the interval of 1.5–3.0 h, a decrease in product moisture content to approximately 6 % is observed.

During this period, moisture transitions from the solid phase to the vapor phase, accompanied by moisture removal from the product.

In the following interval (3.0–5.5 h), the moisture content continues to decrease to approximately 2.8 %, indicating the completion of the primary sublimation stage and the removal of most of the free moisture.

At the final stage of the process (5.5–7.0 h), corresponding to the secondary drying stage, the reduction in moisture content occurs more slowly, reaching a final value of approximately 1.8 %.

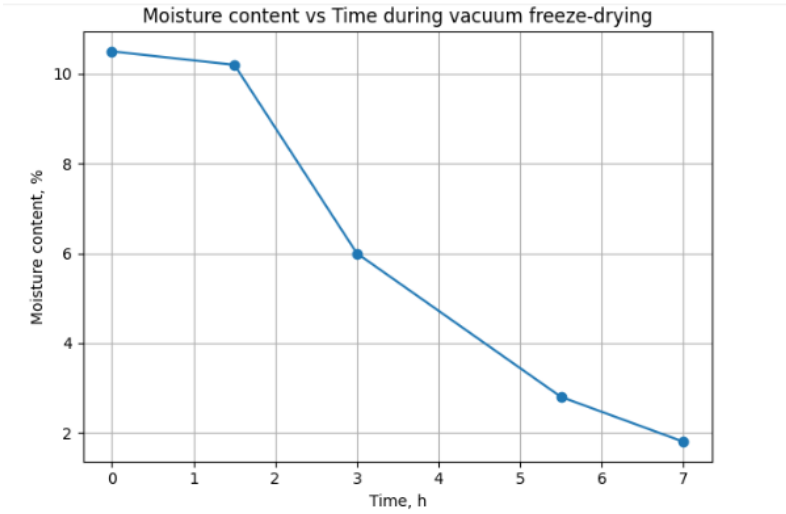

Fig. 10. Change in Product Moisture Content Over Time During Vacuum Freeze-Drying

The obtained relationship confirms the correctness of the selected temperature-vacuum operating conditions.

Comparison of the Proposed Unit with Conventional Solutions

The diagram presents a comparative analysis of the proposed unit and conventional vacuum drying systems based on the main technical and energy performance indicators. These include installed electrical power, specific energy consumption per drying cycle, productivity, and the duration of the technological cycle (Figure 11).

The presented comparative diagram clearly demonstrates the advantages of the developed unit compared with traditional technical solutions. It is shown that the proposed unit is characterized by a significantly lower installed electrical power of up to 6.5 kW, which enables its operation from a single-phase 220 V electrical network without the need for connection to industrial three-phase power sources.

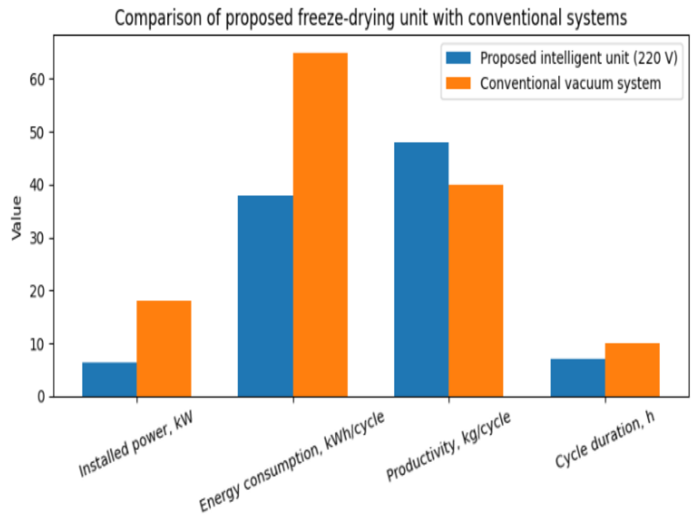

Fig.11. Comparison of the proposed intelligent vacuum freeze-drying unit (single-phase 220 V power supply) and a conventional industrial vacuum drying system based on the main technical and energy performance indicators

It is shown that, with a product load of 45–50 kg, a reduction in energy consumption per drying cycle is observed. The shortening of the technological cycle duration confirms the effectiveness of the implemented algorithm for sequential control of the main system units.

Time diagram of sequential load control

The presented diagram (Figure 12) shows the sequence of control of the compressor, cooling system, vacuum pump, and heating system. The color coding reflects the operating modes of individual units at different stages of the drying process. The bottom row of the diagram represents the compressor of the refrigeration system. The blue color (0–1.5 h) corresponds to the stage of preliminary cooling and product freezing. The orange color (1.5–3.0 h) characterizes compressor operation during the formation of the vacuum regime. The green color (3.0–5.5 h) indicates the maintenance of a stable condenser temperature during the main stage of vacuum freeze-drying.

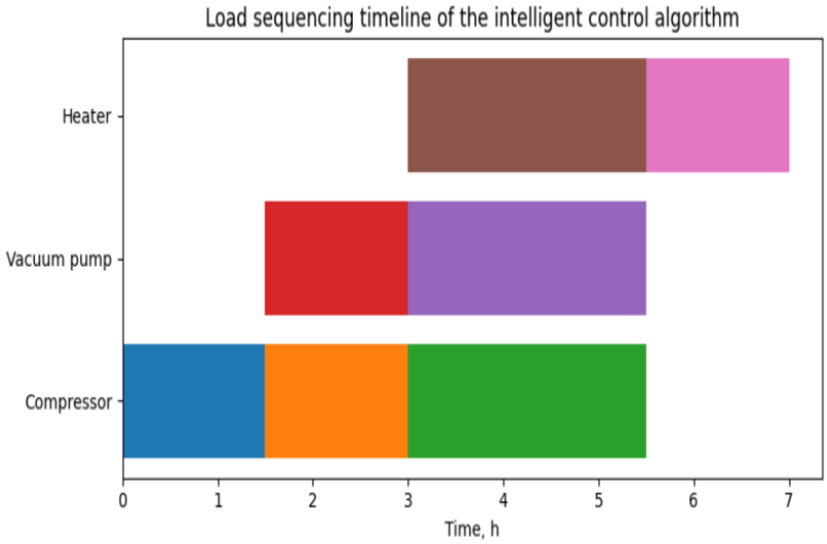

Fig. 12. Time Diagram of Sequential Load Control of the Intelligent Vacuum Freeze-Drying Unit

The middle row of the diagram corresponds to the vacuum pump. The red color (1.5–3.0 h) indicates the stage of vacuum creation in the chamber, while the purple color (3.0–5.5 h) represents maintaining stable pressure during the main sublimation process. The upper row shows the heating system. The brown color (3.0–5.5 h) corresponds to heat supply to the product during the main stage of vacuum freeze-drying, while the pink color (5.5–7.0 h) reflects the final drying stage. The diagram demonstrates the step-by-step activation of actuating mechanisms in accordance with the PLC algorithm logic 0–1.5 h-the refrigeration system operates; 1.5–3.0 h-the compressor and vacuum pump operate simultaneously, 3.0–5.5 h-the heating system is additionally activated; 5.5–7.0 h-final drying is performed with the vacuum pump switched off.

The presented time diagram confirms the correct implementation of the sequential load control principle, which ensures limitation of electrical power consumption and stable operation of the vacuum freeze-drying unit powered from a single-phase 220 V supply network.

Discussion of Results.

The results of vacuum freeze-drying of goat milk obtained during experimental studies on a unit equipped with an inverter compressor and sequential control of electrical loads are explained by the influence of the selected temperature-vacuum operating modes and the design features of the installation. The temperature and vacuum parameters at the main sublimation stage remain stable due to the implementation of a sequential load control algorithm. Maintaining the condenser surface temperature within the range of –46 to –48 °C ensured efficient vapor capture and prevented pressure increase in the vacuum chamber. High values of the relative moisture content difference $\Delta w_{c,rel}$>95 % indicate deep dehydration of the product. Unlike conventional systems requiring a three-phase 380 V power supply, the proposed unit ensures stable operation from a single phase 220 V network due to the integration of an inverter compressor and a sequential control algorithm for energy-intensive units.

Prospects for further research are associated with expanding the experimental database, developing a mathematical model of the process, and adapting the control algorithm to various types of food raw materials. Overall, the results confirm the scientific validity and practical feasibility of the proposed freeze-drying (lyophilization) unit. Explanation of the obtained results. The stability of temperature and vacuum parameters during the primary sublimation stage (Figures 4–7, Table 1) is ensured by the coordinated operation of the refrigeration system, vacuum pump, and heating system, implemented through a sequential load control algorithm (Figure 11). Maintaining the condenser surface temperature within the range of –46 to –48 °C (Figure 5) ensured effective capture of sublimated moisture vapors and prevented pressure increase in the vacuum chamber, which is confirmed by the pressure data p_2 presented in Table 1 and Figure 6.

The intensive reduction in product mass and moisture content during the primary sublimation stage (Figures 8 and 9) is explained by the realization of the direct phase transition "ice-vapor" while maintaining the product temperature below the ice melting point and pressure corresponding to the stable sublimation region. During the secondary drying stage, the decrease in moisture content slows down, which is associated with the removal of bound moisture and a reduction in mass transfer intensity, consistent with classical concepts of vacuum freeze-drying kinetics.

High values of the relative moisture content difference $\Delta w_{c,rel}$ (Table 4), exceeding 95 %, indicate deep dehydration of the product while maintaining the stability of the technological regime, which confirms the correctness of the selected parameters for controlling thermal and vacuum flows. Comparison with existing studies and features of the proposed approach. The obtained results are consistent with the data presented in studies, which demonstrate the high efficiency of vacuum freeze-drying in terms of preserving food product quality. At the same time, most known studies employ installations with high installed power and three-phase 380 V power supply, which significantly limits their application in small and medium-scale production conditions.

In contrast to the solutions described in studies [Chen et al., 2024], where inverter compressors are mainly considered as components of refrigeration systems without accounting for the overall energy structure of the installation, the present study implements an integrated approach combining an inverter compressor with a sequential control algorithm for all energy-intensive units. This made it possible to ensure stable operation of the installation when powered from a single-phase 220 V electrical network without the occurrence of peak loads, which fundamentally distinguishes the proposed technical solution from conventional vacuum freeze-drying systems.

Additionally, unlike certain studies [Lozano et al., 2014: 703–707], where sequential load control is analyzed in a fragmented manner, this work demonstrates its systemic influence on the thermal, vacuum, and energy balance of the installation under increased product loading up to 45–50 kg.

Research Limitations. It should be noted that the results of this study were obtained using a laboratory-scale installation and during the drying of only one type of product-goat milk. The applicability range of the obtained data is limited by a loading capacity of up to 45–50 kg, a heating temperature range of up to 60 °C, and operating conditions powered by a single-phase 220 V electrical supply. In addition, the experimental studies were conducted under controlled laboratory conditions, which ensured high reproducibility of the results; however, they do not account for possible fluctuations in environmental parameters and power supply quality that are typical of real industrial facilities.

Study limitations and ways to overcome them. The shortcomings of the present study include the limited number of experimental series and the absence of an analysis of the influence of the composition and structure of other types of food raw materials on the efficiency of the freeze-drying process. Furthermore, the study did not address issues related to system scaling or the long-term reliability of the installation during continuous operation.

The identified limitations can be overcome by expanding the experimental database, incorporating various types of products (meat, berries, and plant-based raw materials) into the research, and conducting long-term endurance testing of the installation under conditions close to industrial operation.

Future research development is associated with the creation of a mathematical model of the vacuum freeze-drying process that considers the dynamic redistribution of electrical loads and heat flows. Particular interest lies in adapting the control algorithm to different product types and drying modes, as well as implementing predictive and adaptive control elements based on machine learning methods. Potential challenges in further studies include the complexity of heat and mass transfer processes under varying vacuum conditions, as well as the increasing volume of experimental data requiring statistical processing and validation.

Overall, the obtained results confirm the scientific validity and practical potential of the proposed intelligent vacuum freeze-drying installation, especially for applications in conditions of limited electrical infrastructure and single-phase 220 V power supply.

Use of Artificial Intelligence Tools

During the preparation of this manuscript, the authors used the ChatGPT language model (OpenAI, USA) to assist in language editing, text structuring, and improvement of academic style. The artificial intelligence tool was used only to support the writing process and did not participate in the research design, data collection, experimental procedures, data analysis, or interpretation of results. All scientific content, experimental data, analysis, and conclusions were developed and verified by the authors. The authors take full responsibility for the accuracy, originality, and integrity of the manuscript.

Conclusion.

An intelligent freeze-drying installation with an inverter compressor has been developed and experimentally validated. The installation provides drying of products with a mass of up to 45-50 kg and ensures stable temperature-vacuum operating conditions when powered from a single-phase 220 V electrical network.

A sequential control algorithm for energy-intensive system components has been implemented, allowing the peak power consumption to be limited to 6.5 kW, which has been experimentally confirmed.

It has been established that, with increased product loading during the primary sublimation stage, the pressure in the vacuum chamber stabilizes within the range of 45–55 Pa, while the condenser temperature is maintained at 46 to 48 °C.

The main thermal, vacuum, and mass transfer parameters of the vacuum freeze-drying process, ensuring stable realization of the direct phase transition “ice-vapor” have been determined.

Experimental drying of goat milk demonstrated a final moisture content of 1.8–4.2 % and a relative moisture removal efficiency exceeding 95 %, confirming the high efficiency of the process.

Comparative analysis showed that the developed installation has lower installed power and energy consumption compared to conventional three-phase systems and can operate from a single-phase 220 V power supply.

The obtained results confirm the feasibility of applying the intelligent vacuum freeze-drying installation under conditions of limited electrical infrastructure typical for small and medium-scale production facilities.

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