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ANALYSIS OF THE POSSIBILITIES OF INCREASING THE ENERGY EFFICIENCY OF ABSORPTION REFRIGERATION APPLIANCES THROUGH THE USE OF REFRIGERATING ACCUMULATORS

One of the most important tasks of modern society is the solution of environmental and energy problems in power engineering and, in particular, refrigeration technology. At the same time, in the field of artificial cooling systems, it is necessary to solve the problems of reducing the impact on both the ozone layer and the greenhouse effect. An effective approach here can be absorption refrigeration systems with a natural working fluid (water-ammonia solution), which does not adversely affect the environment. For the effective use of absorption refrigeration systems, it is necessary to solve the problems of increasing their energy efficiency, in particular, through the use of cold accumulators. Thus, the object of research is absorption-type cooling systems with cold accumulators.

The paper analyzes cold accumulators with different physical nature. It is shown that melting substances can be the most effective for solving problems of low-temperature cooling. An analysis of the thermal scheme of an absorption freezer of the «chest» type, which is the most problematic in terms of providing cooling modes at a level of (–18)–(–24) °C, was carried out. Optimization thermal calculations for typical absorption freezers up to 200 dm^3 have been performed. It is shown that when the chamber is initially loaded with a product at an ambient temperature, the cooling capacity of the installed absorption refrigeration units is not enough – no more than 50 % of the required one. For an absorption freezer of the «chest» type, the most suitable cold-storage materials are a eutectic aqueous solution of sodium chloride or propylene glycol, since these solutions have the desired melting point of the order of –18 °C and a fairly high melting heat. The result of optimizing the weight and size characteristics of the internal volume of the absorption freezer is the following recommendations:

– the optimal size of wire baskets for placing products is 315×370×240 mm;

– the gaps between the basket and the cabinet wall, as well as between the baskets themselves, should be 10 mm to ensure normal convection conditions;

– it is not advisable to place fans inside the volume of the freezer at this stage, since the freezing time is reduced by a maximum of 30 %, but this results in additional heat generation, energy consumption and increases the shrinkage of the products stored in the chamber.

Keywords: *environment, absorption refrigeration, ozone reduction, absorption freezer. cold accumulator, energy efficiency.*

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1. Introduction

At present, human activity has already reached a level at which its impact on the natural environment is becoming global. Over the past century, the content of some natural gases (CO_2, N_2O, CH_4) in the atmosphere has been constantly increasing. Additionally, gases that are not natural components of the global ecosystem were released into the atmosphere. Chief among them are fluorochlorohydrocarbons (freons). These gases actively absorb solar radiation reflected from the Earth's surface and contribute to the formation of the «greenhouse» effect [1–5].

The current situation forces the developers of household refrigeration equipment to reconsider their attitude to absorption refrigeration appliances (ARA), in the future, in accordance with existing regulatory requirements and definitions [6] – absorption refrigerators and freezers. Such devices are equipped with absorption refrigeration

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units (ARU) and can be considered as one of the alternative options for switching to environmentally friendly refrigerants.

The ARA working fluid consists of natural components – a water-ammonia solution with the addition of an inert gas (hydrogen, helium or a mixture thereof) and is absolutely environmentally safe – it has zero values of the ozone-depleting potential and the potential of the «greenhouse» effect [7].

ARUs also have a number of such unique qualities as [8–11]:

a) noiselessness, high reliability and long service life, absence of vibration, magnetic and electric fields during operation;

b) the possibility of using several energy sources in one apparatus, both electric and alternative (the calorific value of organic fuel, solar radiation, exhaust gases of internal combustion engines, the «hot» air flow of the vortex tube, heat-loaded elements of radio-electronic equipment);

c) the ability to work with low-quality energy sources, including electrical energy, in the mains voltage range of 160–240 V.

The advantages of ARU include lower cost compared to compression analogues, which in many cases determines their popularity among users.

At the same time, ARUs, like compression analogues, are characterized by increased energy consumption during the period of loading products into the useful volume of a cooling or freezing chamber [12]. This is due to the operation of the refrigeration unit in the intensive cooling mode to ensure the standard temperature level in a set period of time. To implement the intensive cooling mode, modern refrigeration units switch to increased energy consumption, which increases the cost of operating a household refrigeration appliance. At the same time, as experience shows [13], under operating conditions with elevated ambient temperatures, even the intensive operation of the refrigeration unit does not allow cooling to standard temperatures within a specified period of time. This problem is especially significant for ARUs, which have a lower, compared to compression analogues, ability to boost cooling capacity [14].

One of the ways to solve this problem can be cold accumulators installed in the useful volume of the cooling or freezing chamber.

It is known that the thermal modes of operation of a refrigerating or freezing chamber are characterized by extreme unevenness: after loading products with ambient temperature until they are frozen, the need for cold is maximum. When the product reaches the required temperature and during storage, cold is needed only to compensate for heat gains through the enclosures of the chamber. Special problems are created during the operation of low-temperature chambers – freezers, in which the temperature difference between the air in the room and in the chamber is, on average, 50 °C.

The amount of accumulated heat (cold) per unit of matter depends on the nature of the accumulation. In the literature [15], thermodynamic parameters are given that make it possible to estimate the values of the amount of accumulated heat for various methods of accumulation:

a) values of the heat capacity of a substance in the solid state: 7.6–28.5 J/(mol·K);

b) values of the heat capacity of a substance in the liquid state: 11.8–33.6 J/(mol·K);

c) values of the specific entropy of melting: 8.4–46.2 J (mol·K);

d) values of the specific entropy of evaporation: 87 J/(mol·K);

e) values of specific heat of fusion: 6.3–14 kJ/mol;

f) values of specific heat of vaporization: 26 kJ/mol;

g) values of specific heat of decomposition: 154.5–174.7 kJ/mol.

An analysis of the given numerical values of the quantities shows that the accumulation of heat by consumable batteries is an order of magnitude higher than that of non-performing phase transitions, and for evaporating batteries it is 3–5 times higher than for consumable ones.

In refrigeration, melting cold accumulators are usually used due to their ease of use and a fairly high degree of cold accumulation. The most widespread are ice-salt solutions with a eutectic salt concentration corresponding to the cryohydrate point, the so-called eutectics. Eutectics are a homogeneous mixture of ice and salt and have a low melting point, which depends on the nature of the salt, as well as a rather high melting heat (Table 1) [16].

Table 1

Thermodynamic parameters of some eutectics

Name of salt	Mass fraction of salt in solution, %	Solution density, kg/m^3	Melting point, °C	Specific heat of fusion, kJ/kg	Specific heat capacity of the solution, kJ/(m·K)
Sodium sulfate	3.8	1030	–1.2	336	3.4
Zinc sulfate	27.2	1250	–6.5	214	3.2
Potassium chloride	19.3	1150	–11.1	299	3.3
Sodium chloride	23.1	1170	–21.2	237	3.3
Calcium chloride	29.9	1280	–55.0	213	2.6

Eutectic ice is also obtained from an aqueous solution of propylene glycol. The melting point of such ice depends on the mass fraction of propylene glycol and varies over a wide range of temperatures (from –3 to –50 °C).

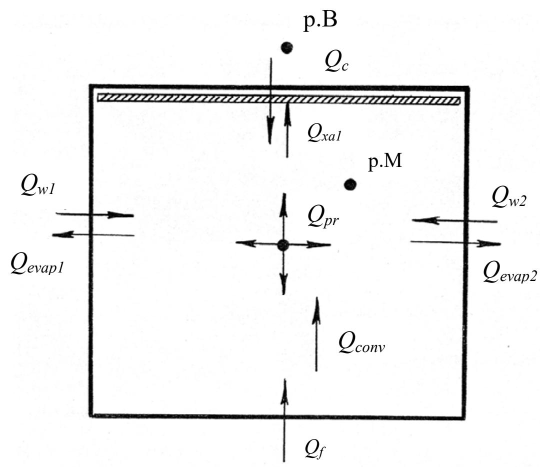
90–94 % of the volume of metal containers of various shapes is filled with a solution of propylene glycol. After freezing the solution at a temperature below the melting point, the containers are placed in a cooled volume.

The purpose of this study is to develop a methodology for calculating the thermal conditions of low-temperature absorption refrigeration appliances with cold storage elements. Such a technique should take into account the features of the implementation of the absorption-diffusion refrigeration cycle (low cooling capacity [17]) and make it possible to find the optimal (according to standard temperature conditions) geometric parameters of the cooling structure elements.

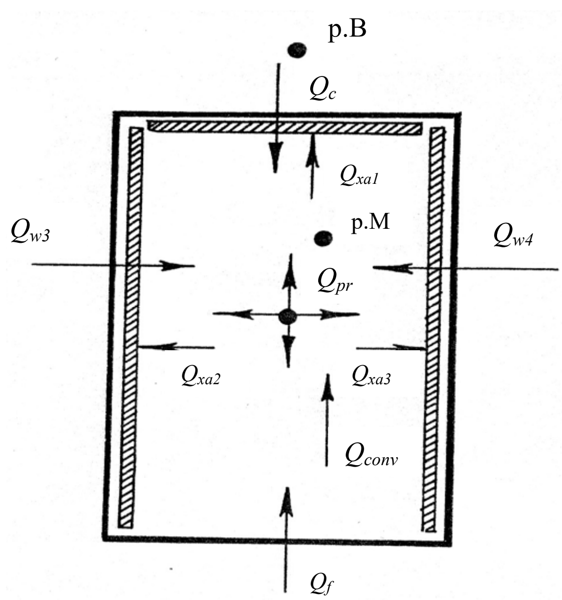
2. Materials and Methods

When analyzing the thermal diagram of the absorption freezer chamber (Fig. 1), significant uneven distribution of heat fluxes is obvious. Heat is supplied to the cooled volume through all four walls of the cabinet (Q_{w1}, Q_{w2}, Q_{w3}, Q_{w4}), cover (Q_c), floor (Q_f), from the loaded uncooled product (Q_{pr}). Heat removal is carried out only through two end walls, in which the evaporators of refrigeration units (Q_{evap1}, Q_{evap2}) are located.

Thus, the heat fluxes entering through the end walls of the cabinet are immediately removed through the freezer evaporators, while the air near these walls does not have time to warm up. Heat flows through the front and rear walls and the floor heat the air inside the cabinet, which rises as a result of natural convection (Q_{conv}). A similar process occurs with the heat introduced by the product. Warm air penetrating through the leakage of the chamber cover accumulates in the upper part of the useful volume of the cabinet and practically does not mix with the rest of the air volume.



a



b

Fig. 1. Thermal diagram of the cooling chamber:
a – front view; *b* – side view

Cold air from the evaporators descends to the bottom of the cabinet.

When using cold-storage materials, temperature gradients by volume are significantly reduced. Cold storage elements should be placed on the front and rear vertical walls of the cabinet, as well as in the freezer lid, as shown schematically in Fig. 1. In this case, there is a uniform heat removal, which does not allow the formation of stagnant zones of warm air in the central and upper parts of the cabinet.

3. Results and Discussion

In accordance with the technical requirements for absorption refrigeration appliances [17], the freezing power of products should be at least 1.00 kg/day for every 10 dm^3 of freezer volume. So, for example, for a freezer with a volume of 200 dm^3, a cooling capacity is required to freeze 20 kg/day of the product.

The amount of heat removed for freezing food products was determined by the equation:

$$Q_{pr} = m \cdot \left(h_s - h_f\right), \quad (1)$$

where m – the mass of the frozen product, kg/day; h_s – specific enthalpy of the product at a temperature of 35 °C, kJ/kg; h_f – specific enthalpy of the frozen product at –18 °C, kJ/kg.

The results of calculations according to equation (1) for various food products subjected to freezing are presented in Table 2.

Table 2

Results of calculations according to equation (1)

Product	h_s, kJ/kg	h_f, kJ/kg	Q_{pr}, kJ/day
Beef meat, poultry	345.0	4.6	6808
Mutton	334.0	4.6	6588
Pork	317.8	4.6	6264
Meat offal	384.0	5.0	7580
Skinny fish	388.0	5.0	7660
Oily fish	369.0	5.0	7280
Butter	240.0	3.8	4724
Ice cream	344.6	7.1	6750

Thus, for the most severe freezer operating conditions, it is necessary to remove 7660 kJ of heat per day or 89 W.

The average refrigeration power of the evaporators of a typical freezer is 60 W, the heat gain through the cabinet walls is 22.4 W. Consequently, the amount of heat removed by the refrigeration units from the loaded products will be 38.6 W.

In order to provide the required freezing power under the most severe operating conditions, the cold storage elements must remove approximately 50 W of heat from the loaded products. If sodium chloride eutectic is used as a cold storage material (Table 1), then it will require 18.6 kg (taking into account only the heat of fusion) to obtain the missing cold. This amount of cold storage material can be placed on two vertical walls and the lid of the freezer cabinet (total area – 1.247 m$^{2)}$ with a layer thickness of 12 mm.

Let's consider freezers made in the form of a «chest» developed jointly by the Odessa National University (Ukraine) and the Vasylkov Refrigerator Plant (Vasylkov, Kyiv region, Ukraine) [10] (Fig. 2).

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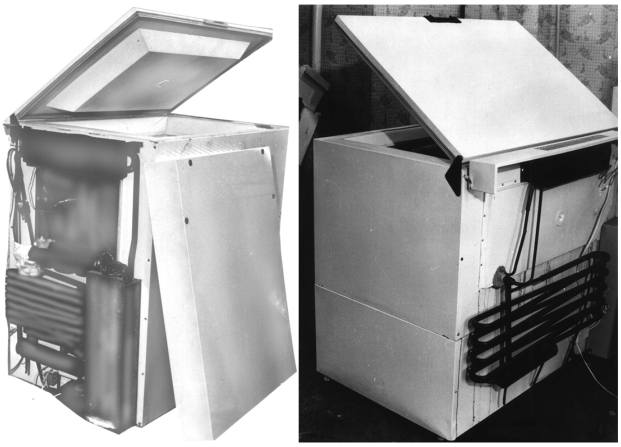


a *b*

Fig. 2. Absorption type freezers:
a – with the end position of two standard ARA; *b* – ARA with increased cooling capacity on the rear wall of the chamber

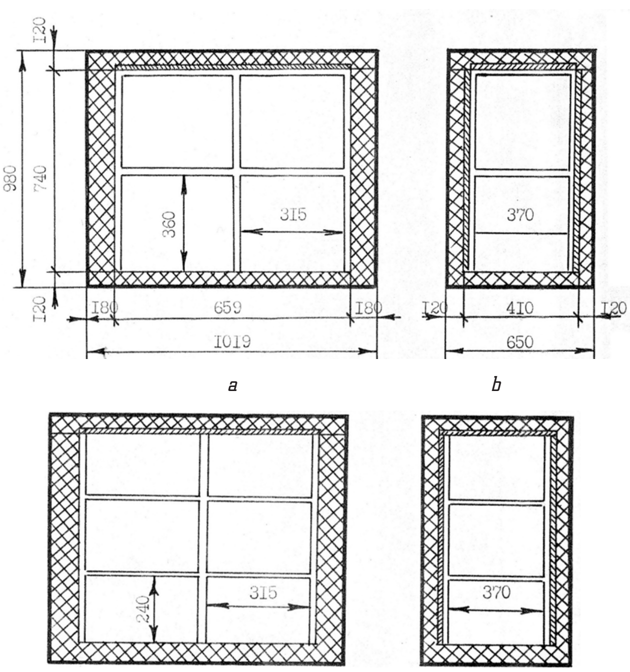
Products are placed in them in hanging wire baskets. Basket sizes should be optimized for the following:

– ease of use by the consumer;

– the consumption of metal from which the baskets are made;

– from the conditions for ensuring effective internal convective heat transfer.

A freezer with a volume of 200 dm^3 has internal dimensions of 0.659×0.410×0.740 m (Fig. 3). From the conditions of ease of use and minimum metal consumption, grids with dimensions in plan are optimal – half the length of the cabinet – the width of the cabinet. The height of one mesh can be one third or half the height of the freezer cabinet and must be optimized to ensure heat exchange on the surface and inside the product.



a *b*

c *d*

Fig. 3. Diagram of the freezer:
a, b – with two baskets in height; *c, d* – with three baskets in height;
a, c – front view; *b, d* – side view

To ensure normal convective heat transfer between the grids, as well as between the grid and the cabinet wall, there must be gaps of at least 10 mm. Based on the foregoing, the mesh dimensions (i. e., the maximum dimensions of a single piece of the product) can be 315×370×240 mm, or 815×370×360 mm. For these two options, the freezing time of the product was calculated under various conditions of convective heat transfer. Beef meat of medium fatness was chosen as a product sample for calculations, since it has the most reliable data on its physical properties.

Fans are widely used in modern freezers to increase the rate at which the product freezes. Appropriate calculations were carried out both for the conditions of natural convection and for forced convection at an air velocity of 1 to 3 m/s.

The coefficient of convective heat transfer for free convection was determined by the known equations [18]:

$$\alpha = \frac{Nu \cdot \lambda}{l}; \tag{2}$$

$$Nu = C \cdot (Gr \cdot Pr)^n \cdot \left(\frac{Pr}{Pr_c}\right)^{0.25}; \tag{3}$$

$$(Gr \cdot Pr) = g\beta \cdot \frac{\Delta T \cdot l^3}{\nu^2} \cdot Pr, \tag{4}$$

where α – the coefficient of convective heat transfer, W/(m^2·K);

Nu – the Nusselt number;

λ – coefficient of thermal conductivity of air; λ=0.023 W/(m·K);

l – the characteristic size of the washed surface;

C, n – coefficients taken according to the table depending on the size of the complex (Gr·Pr); C=0.75, n=0.25;

Gr – the Grashof number;

Pr – the Prandtl criterion for air at the chamber temperature; Pr=0.73;

Prc – the Prandtl criterion for air at product temperature; Prc=0.71;

ΔT – the temperature difference between the surface of the body and air, K;

ν – coefficient of kinematic viscosity of air, m^2/s;

$\beta=1/T$ – coefficient of volume expansion of air, 1/K; $\beta = 0.00392\ 1/K$;

T – air temperature in the freezer volume, K;

g – the free fall acceleration; g=9.81 m/s^2.

The physical properties of the air were chosen at the temperature of the air in the freezer T=255 K.

The heat transfer coefficient α was calculated for each surface separately. In this case, for vertical walls, in accordance with the recommendations [19], the height of 240 mm and 360 mm was taken as the characteristic dimension, for horizontal surfaces, the smaller side of 315 mm. For the upper horizontal surface, the value of α was calculated as for vertical walls, and for the lower one, according to the ratio $\alpha=0.5\cdot\alpha_{vert}$.

The average heat transfer coefficient of the entire surface of the product was determined by the equation:

$$\alpha_F = \frac{\alpha_1 F_1 + \alpha_2 F_2 + \ldots + \alpha_6 F_6}{\sum_{i=1}^{6} F_i}, \tag{5}$$

where $\alpha_1, \alpha_2 \ldots \alpha_6$ – the local heat transfer coefficient of the 1, 2–6th surface of the parallelepiped; $F_1, F_2 \ldots F_6$ – the area of the 1, 2–6th surface of the parallelepiped.

Using this method, the heat transfer coefficients were calculated for the initial surface temperature of the product of 35 °C and the final temperature of minus 18 °C; in further calculations, the arithmetic mean of the convective heat transfer coefficient was used:

a) at a height of 0.24 m α=4.9 W/(m²·K);

b) at a height of 0.36 m α=4.6 W/(m²·K).

The coefficient of convective heat transfer under forced convection was determined by the equation [11]:

$$Nu = 0.664 \cdot Re^{0.5} \cdot Pr^{0.33} \cdot \left(\frac{Pr}{Pr_c}\right)^{0.25}; \tag{6}$$

$$Re = \frac{w \cdot l}{\nu}, \tag{7}$$

where Re – the Reynolds number.

Equation (6) is applicable for laminar conditions of flow around the surface, which are performed at an air speed of 1–3 m/s. The maximum length of the parallelepiped rib (l=370 mm) was taken as the determining size.

The values of the coefficient of convective heat transfer under forced convection for various air velocities are obtained:

– air velocity 1 m/s, α=6.4 W/(m²·K);

– air velocity 2 m/s, α=9.1 W/(m²·K);

– air velocity 3 m/s, α=11.1 W/(m²·K).

The passport duration of meat freezing is the time required to lower the temperature in the thickness of the meat from plus 35 °C to minus 8 °C. Experimental studies of the dependence of temperature in the thickness of meat on time during freezing show that the freezing process can be divided into three stages:

1) meat cooling to 0 °C;

2) freezing the moisture contained in the meat (from 0 °C to minus 1 °C);

3) cooling the frozen meat to the temperature in the freezer.

Due to the fact that the physical properties of meat differ significantly depending on the moisture content and fat content, and also due to the lack of data on the properties of meat at low temperatures in the literature, it is not possible to accurately calculate the freezing time of meat using theoretical methods. As a first approximation, the meat freezing time was calculated according to the data on the properties at positive temperatures without taking into account the phase transition. At the same time, the calculated curve corresponding to the first stage of meat cooling in Fig. 4 is extrapolated to the region of low temperatures. The calculation errors that arise with this approach partially compensate each other as a result of the fact that the cooling rate during the phase transition will be lower, and when the frozen meat is cooled, it will be higher than the calculated one. To determine the exact freezing time of a single block of various products, it is necessary to conduct a full-scale experiment in a prototype freezer.

The calculation of the cooling time of a block of meat to a temperature of minus 8 °C in the center of the block at different heat transfer coefficients on the surface of the meat was carried out according to the method [20]. The calculation of the temperature field for a parallelepiped is based on the theorem of solution multiplication: the dimensionless temperature of a body of finite dimensions is equal to the product of the dimensionless temperatures of one-dimensional bodies, the intersection of which forms a body of finite dimensions.

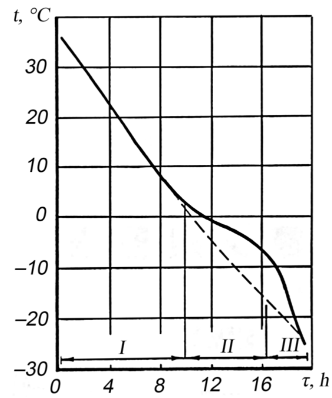


Fig. 4. Temperature in the thickness of the thigh during single-phase freezing of a beef side carcass: I – meat cooling; II – moisture freezing; III – cooling of frozen meat approximation of the cooling curve to the region of negative temperatures

The meat block, represented as a parallelepiped, is formed by the intersection of three infinite plates with thicknesses $2\delta_x$, $2\delta_y$ and $2\delta_z$, therefore, its dimensionless temperature can be represented as a product of three factors:

$$\theta = \left[T(x,y,z,\tau) - T_l\right] / (T_0 - T_l),$$
$$(x,y,x,\tau) = \theta_x(x,\tau) \cdot \theta_y(y,\tau) \cdot \theta_z(z,\tau); \tag{8}$$

$$\theta_x = \frac{T(x,\tau) - T_l}{T_o - T_l}; \tag{9}$$

$$\theta_u = \frac{T(y,\tau) - T_l}{T_o - T_l}; \tag{10}$$

$$\theta_z = \frac{T(z,\tau) - T_l}{T_o - T_l}, \tag{11}$$

where θ – the dimensionless temperature; $\theta_x, \theta_y, \theta_z$ – the dimensionless temperatures of three infinite plates with thicknesses $2\delta_x$, $2\delta_y$ and $2\delta_z$; $T(x,y,z,\tau)$ –temperature at the point of the parallelepiped with coordinates x, y, z at the moment of time τ, K;

The dimensionless temperature $\theta_k(k = x,y,z)$ for each of the plates is calculated as a function of the dimensionless coordinate k/δ_k, Biot number $Bi_k = \alpha\delta_k/\lambda$ and Fourier number $Fo_k = a \cdot \tau / \delta_k^2$ according to the corresponding equations.

With numerical values $Fo \geq 0.3$, the change in temperature time on the middle plane of the plate x=0 is described by the equation:

$$\theta o = N(Bi) \cdot \exp(-\mu_1^2 \cdot Fo), \tag{12}$$

where the values of N and μ_1^2 depending on the number Bi are tabulated and given in [1].

Using equations (8)–(12), the dimensionless temperatures at the center of the parallelepiped were calculated. The values used in the calculations are given in Table 3.

Table 3

Quantities used in calculating the dimensionless temperature at the center of the parallelepiped

Value name	Designation	Units	Numerical value
Endless plate thickness	δ_x	m	0.315
	δ_y	m	0.370
	δ_{z1}	m	0.240
	δ_{z2}	m	0.360
Coefficient of convective heat transfer on the surface of a parallelepiped	α	W/(m^2·K)	Presented above in the text
Average thermal conductivity of meat	λ	W/(m·K)	0.49
Average coefficient of thermal diffusivity of meat	a	m^2/s	15.8·10^{-8}
Air temperature in the freezer	T_l	K	255
Surface temperature of the parallelepiped at the initial moment of time	T_0	K	308

As a result of calculations using the above method, the time required to lower the temperature in the center of the parallelepiped to minus 8 °C (freezing time) was determined, which is given in Table 4.

Table 4

Freezing time of meat at different heights of the parallelepiped and coefficients of convective heat transfer

Convective heat transfer coefficient, (W/(m^2·K))	Parallelepiped height, m	
	0.240	0.360
4.6	–	35
4.9	28	–
6.4	24.4	30.9
9.1	21.1	27.2
11.1	19.6	25.3

An analysis of the temperature and energy characteristics of an absorption freezer shows that when the chamber is initially loaded with a product at an ambient temperature, the cooling capacity of the installed ARA is not enough – no more than 50 % of the required one. This discrepancy is the result of a relatively large usable volume of the freezer and a relatively small cooling capacity of the installed ARA at a temperature level of (–18)–(–24) °C. However, this shortcoming is significant only at the time of initial loading of the freezer, and the most realistic means of overcoming it can be the use of cold storage materials.

Of particular interest from the existing variety of cold-storage materials are aqueous solutions of salts and glycol due to their low cost and wide use in technology. In particular, for the considered absorption freezer, the most suitable cold-storage materials are the eutectic aqueous solution of sodium chloride or propylene glycol, since these solutions have the desired melting point of the order of minus 18 °C and a sufficiently high melting heat. To reduce the high corrosivity of these solutions, it is necessary to use chemical protectors to maintain the brine in a neutral state (pH7), while closed-type brine systems can operate for decades.

When using cold storage materials in the freezer, one essential requirement arises – when the freezer is initially turned on, it takes time to freeze the cold storage.

It is known [14] that at the designed height of the freezer cabinet, the unevenness of the temperature field along the height is at least 5–7 °C, thus, cold-storage elements, which significantly reduce temperature gradients, significantly increase the efficiency of the freezer and improve food storage conditions.

The practical result of the research was the optimization (in terms of the time to reach the required freezing temperature) of the weight and size characteristics of the internal volume of the absorption freezer:

– the optimal size of wire baskets for placing products is 315×370×240 mm;
– the gaps between the basket and the cabinet wall, as well as between the baskets themselves, should be 10 mm to ensure normal convection conditions.

It has also been shown that it is not advisable to place fans inside the volume of the freezer, since the freezing time is reduced by a maximum of 30 %, but in this case, additional heat generation occurs, electricity consumption increases and shrinkage of the products stored in the chamber increases.

Research limitations. The presented results were obtained for a typical, but a single example of the design of an absorption freezer, which currently limits their scope of practical application.

Prospects for further research. For their effective application in design, experimental studies should be carried out on real objects and, if necessary, the calculation method should be adjusted.

The results obtained are especially relevant for the wartime conditions that take place in Ukraine in 2022–2023, taking into account the possibility of implementing the proposed freezing technologies without the use of electrical energy sources [21].

4 Conclusions

1. As a result of the research, the following results were obtained:

– an analysis of the current state of development of cold-storage materials was carried out and their most promising types for refrigeration equipment were identified;
– a method for calculating the temperature fields of products under conditions of their freezing in a limited volume (up to 200 m^3) was developed and the optimal dimensions of the cooling elements and their location relative to each other were determined;
– recommendations have been developed for the optimal modes of freezing products, which take into account the low refrigeration capacity of absorption refrigeration units and the possibility of using cold-storage materials, such as sodium chloride solution or propylene glycol.

2. The research results were obtained using modern concepts of heat transfer processes in a limited space on the example of modern Ukrainian absorption refrigeration equipment.

3. The results obtained can be used in the design of absorption-type freezers for operation in the conditions of small farms and peasant farms.

4. The developed technology for freezing food products using absorption refrigeration units makes it possible to implement it in conditions of complete absence of sources of electrical energy, for example, using biogas burners or any other organic fuel.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

The manuscript has no associated data.

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