Spherical storage facilities as an energy-saving innovation in small business forms

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Abstract. Ensuring food security is a priority for the development of Russian agriculture. In this regard, the increase in the number of refrigeration plants for storing agricultural and other products, which require a significant amount of electric energy to generate cold, necessitates the search and development of new energy-efficient sources of cold supply. The solution to this problem is possible due to the commissioning of fruit and vegetable storages of a buried type of spherical shape. The calculation of heat losses indicates a significant superiority of such fruit and vegetable storages over standard ones - with flat enclosing surfaces, and the use of cold charging of the carrier soil mass contributes to the regulation of the storage mode of products in the optimal range of temperature values, which ensures a long period of quality assurance. Keywords: storage of vegetables and fruits, spherical shape, heat conductivity, heat flow, temperature head, stationary mode.

1 Introduction

Today, the agricultural sector for the production of vegetable products, which is actively developing in the Russian Federation, shows an acute shortage of complex functioning vegetable storage facilities. Nevertheless, according to departmental statistics of the Ministry of Agriculture for July 2023, the total capacity of vegetable storage facilities in Russia was 8,8 million tons. For example, in 2022, potatoes and vegetable storages were in the presence of about 7 million tons, and fruit storage facilities for 450 thousand tons. According to forecasts of experts from the Center for Macroeconomic Analysis and Regional Forecasting of Rosselkhozbank, the commissioning of new modern storage facilities will reduce product losses by 2 million tons by 2025. In turn, market participants believe that in the data of the Ministry of Agriculture, most of the information reflects the state in relation to the storages of personal subsidiary farms, which cannot store crops for longer than two months, and the presented final indicators for 2023 are significantly lower than the harvest of vegetables of open and closed soil, which in 2022 amounted to 13.5 million tons. The modern set of vegetable storages is adequate only 30-40% of the grown crop of vegetables and 10-15% of fruits. At the same time, about one third of the grown crop is consumed during the harvesting season. The prospect of the coming years is the possibility of erecting modern fruit and vegetable storage facilities through the implementation of investment projects providing for

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a state subsidy that covers a quarter of the cost of work on their construction and modernization. The start of the entire process is scheduled from January 1, 2024 [1, 2, 3].

Competition in the agricultural market imposes strict requirements for the quality of products, and, therefore, for storage conditions. Modern vegetable storage allows you to create a favorable microclimate for various types of crops, protect products from adverse external conditions (freezing, overheating, excess moisture), from pests (insects, rodents, mold, fungi), provides control over the biological and bacteriological state of the product during its long storage, thereby eliminating serious losses. However, as practice shows, even a small modern storage facility of up to 250 tons will cost the farmer about 5-10 million rubles, and most farms can't afford their construction [3, 4, 5].

On the territory of the Russian Federation, today, there are still enough Soviet-style vegetable storages - outdated buildings made of brick or concrete, having a different degree of burial, which are no longer able to provide the necessary conditions for storing products, and new modern vegetable storages, as statistics indicate, are being built in very limited quantities. According to the analytical department of the National Fruit and Vegetable Union, modern high-tech storage facilities make up only 20 − 25% of the total capacity, at the same time, old vegetable bases and warehouses make up 50% of all vegetable storage facilities.

Technologies for the construction of old Soviet-style storage facilities from the distant past are practically not adapted to achieve results adequate to the requirements of modern industries. This is especially true for equipping premises with plenum and exhaust ventilation, as well as for the possibility of implementing regulatory methods for storing stored vegetables, great complaints about the lack of automation systems and a low level of quality climate control. However, the immediate re-equipment, at least with the latest climatic systems, will require investments of such an order that it will make further operation of the storage unprofitable, and the return to the previous construction technologies and technologies for the production of building materials, as the economic analysis has already shown, is a procedure not only multi-cost, but also "long-playing." This option by commodity producers, taking into account the modern dynamics of production development, is not considered in principle [4, 5, 6].

Depending on the technologies used, investments in vegetable storage facilities range from 50 to 100 thousand rubles per ton of pledged products. The situation in the modern market is such that simplifying construction projects in order to reduce their cost acquires the features of a kind of "investment anomaly," which in turn exacerbates the problem associated with violation of important sanitary, epidemiological, environmental and fire requirements. As a rule, the result is one - the erected object cannot fulfill the routine technological task set for it to preserve the quality and marketable type of vegetable or other products before the implementation period, and this "strictly" affects the competitiveness of domestic goods [4, 7, 8].

Paying tribute to the storage facilities built back in Soviet times, it should be noted that, with appropriate refinement, it is really possible to store crops, and often quite high quality, but it is very difficult to build warehouse logistics after the renovation, since this is primarily due to the peculiarities of the design solutions used earlier. Advanced solutions of the past cannot at the level of modern production ensure the efficiency of warehouse operations, directly related to the quality of the shipped product, and dominantly affecting its cost. Against this background, the owners of modern high-tech storage facilities win their significant market share, and this, despite the fact that the construction and operation of facilities of this level in the budgetary aspect require significantly large investments. A competent entrepreneur, clearly realizing that the payback period of investments pledged in vegetable storage facilities directly depends on the volume of storage, correlates the economic effect of the future period with the scale of the project implementation of today. As an example, the capacities of complexes from the zero cycle, modernized or reconstructed

funds, allow you to store 5 − 7 thousand tons of vegetables at a time, and such storage facilities pay off on average for a period of four to five years. However, the real fact is that not all farmers can afford the construction of modern vegetable storage facilities, even counting on state support [1, 3, 7, 8].

In connection with the above, the surge in interest in the construction market in new facilities that meet the numerous requirements of modern storage facilities is not surprising. Scrupulously studying the design of the process facility, the customer puts in the terms of reference a list of functions that often go far beyond the technology of high-quality storage of products, that is, the possibility of refinement, packaging, prompt shipment of products, etc., also attracts his attention. All this requires new approaches from design organizations, and from builders, and, of course, from engineers who can offer a rational technical solution within the framework of "reasonable investments." As a result, the fundamental concept of the connection between science and production is updated, when the physical principle of operation and the physical and technical effect underlie the formation and contribute to the rational management of the situation in the modern market.

The purpose of the study is to analyze the prospects for the technical implementation and feasibility of introducing buried fruit and vegetable storages of spherical shape in conditions of small forms of management.

Structurally, the vegetable storage facility is a tank where certain conditions for product safety must be maintained. Withstand parametric standards, for example, for humidity - 75... 95 % or temperature - (-1...+ 5)^{0}C, it is possible not only with the help of "climate control," but also with intensive ventilation, as well as the degree of burial of the vegetable storage. Historical experience confirms that ground storage facilities both abroad and in Russia have become widespread due to the convenient transport connection of the internal volume of the building with external infrastructure, as well as the ability to build them in places with a high groundwater level.

At the same time, storage facilities for a certain type of vegetables, for example, onions, should provide a reduced level of relative air humidity, therefore they were designed only in the ground version. However, in domestic construction practice - more than 50% of the objects of the previous generation were semi-buried. The advantage of semi-deep storages manifests itself only in a stably cold microclimate, since the influence of external temperature differences is minimal, therefore, the air temperature in them in spring and summer is lower than in ground. It is possible to give a similar characteristic to buried storages, but it should be noted that the structures of buried structures are extremely rare, since they were built mainly in areas with a design winter outside air temperature (-30...-40)°C. This caused high risks in case of improper storage, when producers could lose up to 60% of the harvested crop, and the agro-industrial complex - suffered colossal financial losses. By the way, the risks should include a very limited period of preservation of products at underground levels without appropriate technological equipment. However, entrepreneurs have always been attracted by the factor of minimizing thermal insulation materials in relation to vegetable storages of a buried and semi-buried type. Thanks to the use of adequate properties of bearing soils, designers can design a technological underground structure that ensures a stable climatic regime, as well as crop safety during periods of high and low environmental temperatures. In the prolongation of the above, it is necessary to indicate a significant increase in prices for both construction materials and specialized equipment (plenum and exhaust ventilation, automation system, climate control). Moreover, experiments have reliably proven that not only the conditions created in vegetable storages, but also the geometry of the building structure, which significantly affects the creation of these conditions, allow to preserve the crop [4, 7, 8].

Thus, the construction of buried storage, especially resource-saving form, could currently be categorized as a high-tech and innovative solution. The only problem is that engineers will

have to solve a different parametric problem - "energy geometry" - how to achieve a combination of the maximum possible volume of the room with a minimum surface area through which heat can escape.

A solution to this problem should be sought in the "isoperimetric theory" of geometry, according to which among all closed surfaces of a given area there is a surface containing the largest volume, and such a surface in space is a sphere. A room that has the highest isoperimetric coefficient, the best in terms of the ratio of space and surface through which heat escapes. The same situation can be attributed to the cold, since there is cold, nothing more than low potential heat. The isoperimetric coefficient is always less than or equal to one, and the only body having a coefficient equal to one is the ball [9].

The ratio of the surface area of a ball to its volume (S_{sp}/V_{sp}) is an important prerequisite for the integration of science into technical solutions, since this value is used to explain the functional relationships between the structure and the processes implemented in the system of surface and volume characteristics of a parametrically optimized form. One of these processes is thermal conductivity, due to which the temperature regime is controlled, which is reliably described by the thermal conductivity equation. The relationship of the ratio (S_{sp}/V_{sp}) with the diffusion rate or thermal conductivity is considered taking into account the heat flow and the surface of the body as a place where diffusion or thermal conductivity occurs. As a result, the greater the (S_{sp}/V_{sp}) ratio, the greater the surface area per unit volume through which diffusion can pass, and, therefore, the diffusion or thermal conductivity process will be much faster [10].

Figure 1 shows a variant of the technological model of underground storage, which has the advantage that during the implementation of the construction project, its spherical shape implies a significant reduction in material capacity, time and time for the construction of the facility (25-30%). Since the surface of the ball is about a quarter smaller than the surface of a cube of the same volume, to the extent that materials will be consumed on a spherical structure by a quarter less than on a cubic one. In addition, they lack angles that prevent convection and ventilation of the internal cavity. Typically, spherical objects are made seamless, which minimizes heat loss, and heating or cooling systems have higher efficiency. Thus, the capacity of the heating system is 1.5 times less compared to traditional objects, since there are no problem areas with hydraulic resistance to air circulation in a spherical room. A whole-built sphere is much more difficult to destroy. Having a defect of point weakening or concentrated stress, the spherical structure does not lose its formological stiffness and does not fold. The development of architectural and technological "symbiosis" speaks of the expediency of introducing, precisely during the construction of spherical buried storage structures, advanced forced technologies of a geodetic or stratodetic dome.

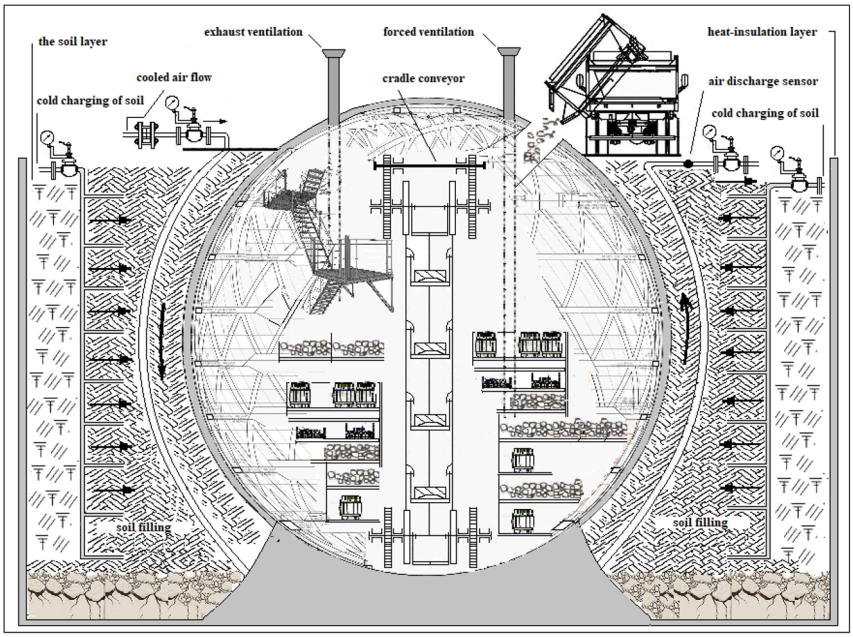

Fig. 1. Process diagram of buried fruit and vegetable storage of spherical shape

The study of the issue of energy efficiency of buried vegetable storages is based on algorithms for calculating heat losses through enclosing structures, as well as on optimizing the temperature of the soil massif charged by cold. But, although the effect of energy consumption reduction is determined and manifested during the operation of cooled bearing soil, the result of analytical procedures should be the justification of technical solutions aimed at the formation of priority technologies and methods of their verification related to the selection of optimal geometric forms of the designed objects.

2 Research methodology

The study of the processes of redistribution of thermal energy through the enclosing surface of a spherical shape involves the analysis of the differential equation of thermal conductivity of the French scientist J. Fourier, obtained by him in 1814.The scientific and practical value is represented by the vector form of recording the differential equation of thermal conductivity:

$$c_{sp}\frac{\partial T}{\partial \tau} = div(\mu q rad T) + q_v, \tag{1}$$

where: $c_{sp} = \rho c$ – specific volumetric heat capacity, J/m^{3}K; ρ – density, kg/m^3 ; c – specific mass heat capacity, J/kgK; q_v – heat effluent capacity, W.

The thermal conductivity equation (1) establishes a relationship between the spatial and temporal temperature changes, and its solution with the given unambiguity conditions allows you to find the temperature field T (x_i,τ) [11, 12, 13].

At the same time, when studying temperature fields, it is advisable to use the Fourier differential equation with constant physical coefficients:

$$\frac{\partial T}{\partial \tau} = \sigma\left(\frac{\partial^2 T}{\partial x_1^2} + \frac{k-1}{x_1}\frac{\partial T}{\partial x_1}\right) + \frac{q_v}{C_{sp}}, \tag{2}$$

where: $x_1 = r$ – coordinate in calculation of heat transfer through spherical wall, m; σ – thermal diffusivity, m^2/s; k – body shape factor (for sphere k = 3), τ – time of thermal conductivity process, s.

As a rule, the internal cavity of the storage is a technical system with no internal heat sources ($q_v = 0$). Then the Fourier differential equation for the sphere is formalized as follows:

$$\frac{\partial T}{\partial \tau} = \sigma\left(\frac{\partial^2 T}{\partial r^2} + \frac{2}{r}\frac{\partial T}{\partial r}\right). \quad (3)$$

Under constant heat exchange conditions, that is, at constant ambient temperature and constant heat transfer coefficient at the boundaries of the body, its temperature field ceases to change over time from a certain moment, and a stationary thermal conductivity mode occurs. It is to be understood that in this case the process is described as having active internal sources of heat (e.g. gas medium from vegetables) by Poisson's equation:

$$\frac{\partial^2 T}{\partial x_1^2} + \frac{k-1}{x_1}\frac{\partial T}{\partial x_1} + \frac{q_v}{C_{sp}} = 0. \quad (4)$$

If $q_v = 0$, then expression (4) takes the form of Laplace's equation:

$$\frac{\partial^2 T}{\partial x_1^2} + \frac{k-1}{x_1}\frac{\partial T}{\partial x_1} = 0. \quad (5)$$

For the convenience of calculating the temperature field in the process of stationary thermal conductivity, equation (5) is advisable to lead to a divergent form of recording:

$$\frac{1}{x_1^{k-1}}\frac{d}{x_1}\left(x_1^{k-1}\frac{dT}{dx_1}\right) = 0. \quad (6)$$

But, since we are talking about the most convenient methodological approach to the study of the heat conduction process, it should be explained that as a result of solving the one-dimensional differential equation for the stationary heat conduction process, a temperature field in the form of $T(x_1)$ or $T(x)$ is found in the Cartesian coordinate system, and T (r) - in the spherical [11, 12, 13, 14].

As for the sphere with a given radius r and the surface area S shown in Figure 2, it is necessary to take into account the condition of the orientation of the temperature gradient along its radius, which allows using the integral form of Fourier's law to work with heat flow:

$$Q = -\mu\frac{\partial T}{\partial r}S, \quad (7)$$

where: Q - heat flux, W; μ – thermal conductivity coefficient, W/(mK); $\frac{\delta T}{\delta r}$ – temperature gradient, K/m; S – surface area of the sphere, m^2 :

$$S = \pi d^2 = 4\pi r^2. \quad (8)$$

With respect to the sphere with internal and external radii r_1 and r_2 , respectively, in order to calculate the heat transfer in a steady state heat exchange mode, the thermal conductivity of the μ=const is prioritized as the most common case in a homogeneous wall material and a stationary one-dimensional temperature field. From the one-dimensional temperature field, it follows that the density of the heat flux, like the heat flux itself, as well as the temperature,

is a function of one variable - the radius r. As a consequence, the temperature of the medium, in this case, is also a function of the variable - radius r (T = T (r)), and isothermal surfaces are concentric spheres [11, 15]. Then:

$$T \neq f(\tau) \text{ и } Q \neq f(x_1, \tau), \quad (9)$$
$$T = f(x_1) \text{ и } Q \neq \text{const}, \quad (10)$$

where: $x_1 = r$ – coordinate in calculation of heat transfer through spherical wall, m.

Since in steady state after some time the temperature inside the sphere will no longer depend on the temperature of the environment, since the amount of heat emitted per unit time inside the spherical surface will be equal to the amount of heat passing through its surface during the same time.

The temperature field changes within the thickness of the spherical wall at a constant thermal conductivity coefficient according to the hyperbolic law:

$$T(r) = T_{s1} - \frac{T_{s1} - T_{s2}}{\frac{1}{r_1} - \frac{1}{r_2}} \left(\frac{1}{r_1} - \frac{1}{r}\right), \quad (11)$$

where: T_{s1} – temperature on the inner surface of the sphere, K, Ts_2 – temperature on the outer surface of the spherical wall, K, Ts_1-Ts_2 – thermal head, K, r – specified radius, m.

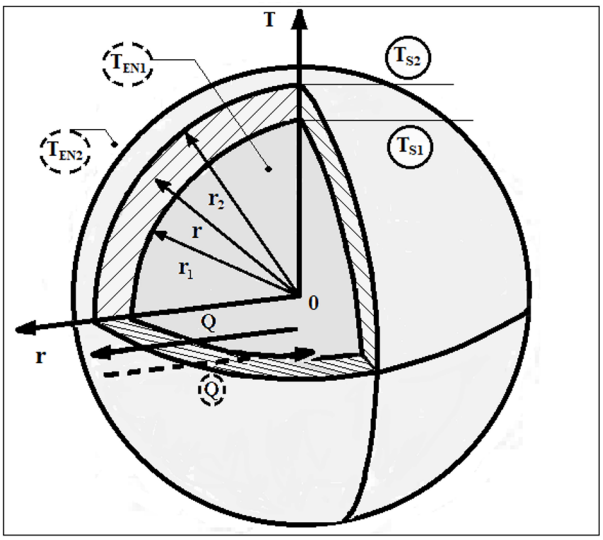

Fig. 2. Diagram of thermal energy redistribution in spherical surface

By substituting a given value of radius r into equation (11), one can determine the temperature T at any point for the spherical surface under study [11, 15].

Value of heat flow Q in spherical wall with inner r_1 and outer r_2 radius is found by Fourier's law (7):

$$Q = -\mu \frac{\partial T}{\partial r} S = -4\mu\pi r^2 \left(-\frac{T_{s1} - T_{s2}}{\frac{1}{r_1} - \frac{1}{r_2}} \left(\frac{1}{r^2}\right) \right);$$

$$Q = \frac{4\pi(T_{s1} - T_{s2})}{1/\mu(\frac{1}{r_1} - \frac{1}{r_2})}. \quad (12)$$

Given that d = 2r, formula (12) is converted into the expression:

$$Q = \frac{\pi(T_{S1} - T_{S2})}{1/2\mu(\frac{1}{d_1} - \frac{1}{d_2})}, \quad (13)$$

where: d_1 и d_2 – inner and outer diameters of spherical wall, m.

Then, the heat flux passing through the multilayer spherical wall can be calculated by the equation:

$$Q = \frac{4\pi(T_{S1} - T_{n+1})}{\sum_{i=1}^{n} \frac{1}{\mu_i}(\frac{1}{r_1} - \frac{1}{r_{i+1}})}. \quad (14)$$

In the case of evaluating transient thermal conductivity, information is needed on the distribution of temperature in the body volume for a certain time point taken as the starting point of time (time point $\tau = 0$) with a given function:

$$T(x,\tau = 0) = T_0\,(x_i) \text{ or } T(x_i, 0) = T_0\,(x_i). \quad (15)$$

For a particular case - the same temperature throughout the body volume at the initial moment of time - accordingly, the initial condition takes the form:

$$T(x_1, 0) = T_0 = \text{const}. \quad (16)$$

But, it should be borne in mind that for stationary thermal conductivity problems, setting the initial condition does not make sense [11, 15].

The boundary conditions of the third kind set the temperature of the external environment surrounding the body and the law of heat exchange between the medium and the surface of the body, which is quite common in practice. The law of heat exchange between the environment and the surface of the body most often in engineering calculations is the law of heat transfer (Newton's law):

$$q_\omega = \alpha \Delta T, \quad (17)$$

where: – heat-transfer coefficient, W/(m^{2}K); $\Delta T = T_{en2} - T_{S2}$ – temperature difference between the environment and the surface of the spherical body, K; T_{en2} – ambient temperature, K; T_{S2} – the temperature of the outer surface of the sphere, K.

As you know, in the general case, heat transfer occurs by convection and radiation.

Using the heat flux density of the q_ω, as well as the boundary conditions of the third kind, taking into account the sign of the temperature gradient and the sign of the temperature difference in the given coordinate system, the basic law of thermal conductivity can be written as:

$$\pm\mu \frac{\partial T}{\partial n} = \alpha \Delta T, \quad (18)$$

where: n – a coordinate directed normal to the body surface.

In thermal conductivity calculations, a dimensionless form of recording the boundary conditions of the third kind is used, which in general has the form:

$$\pm\partial\theta/\partial x = Bi\theta_\omega\,, \quad (19)$$

where: $\theta = \frac{T_{en} - T}{T_{en} - T_0}$ – dimensionless (relatively excessive) temperature; $X = \frac{x_1}{R}$ – dimensionless quantity; T_0 – reference temperature, K; R – defining body size, m; $Bi = \frac{\alpha R}{\mu}$ – Bio criterion (*Biot*).

The physical meaning of the Bio criterion is convenient to reveal by writing it in the form:

$$Bi = \frac{\alpha}{\mu/R}, \tag{20}$$

$$Bi = \frac{R/\mu}{1/\alpha}. \tag{21}$$

Analyzing formula (20), it can be concluded that the Bio criterion characterizes the ratio of external heat exchange intensity (α) to internal heat exchange intensity (λ/R). On the other hand, as shown by formula (21), Bio's criterion characterizes the ratio of thermal thermal conductivity resistance (R/ μ) to thermal heat transfer resistance (1/α) [11, 12, 13, 14].

Thus, the temperature field of the sphere during its heating (cooling) can be determined by solving the boundary problem of the theory of thermal conductivity, which consists of a differential equation and unambiguity conditions. Under the boundary conditions of the third kind, the heat exchange on the surface of the body depends on the ambient temperature T_{en2} and the heat transfer coefficient α

As a result of solving the problem of transient thermal conductivity, a temperature field T (x,τ) is established, which varies in space and time. A uniform initial temperature field, constant physical properties of the body under boundary conditions of the third kind give accurate analytical solutions of the differential equation of thermal conductivity [12].

The process of heating (cooling) the sphere for the case of a temperature field under boundary conditions of the third kind with a constant temperature of the medium T_{en2} and a given heat transfer coefficient α takes place in three stages. In the initial period of heating (cooling), the initial distribution of temperatures over the cross section of the sphere affects the process of forming a temperature field. This is followed by a steady-state or regular mode, followed by a thermal equilibrium mode, in which the temperature of the sphere over the entire section becomes equal to the surface temperature of the body T_{s1}. The regular heating mode of the sphere is characterized by a constant relative heating rate, which is called the heating (cooling) rate. The heating rate does not depend on the coordinates, nor on the time and is equal to:

$$\vartheta = -\frac{1}{\theta}\frac{\partial\theta}{\partial\tau}. \tag{22}$$

Heat exchange at the boundary of a solid is convenient to describe the boundary conditions of the third kind, the most common in the practice of engineering calculations. The analytical solution of the boundary problem (with initial and boundary conditions) in the framework of the theory of thermal conductivity of the sphere for the regular mode is written in the form:

$$\theta_s(x, f_0) = N_s \frac{\sin(\varphi_1 x)}{\varphi_1 x} e^{-\varphi_1^2 f_0}, \tag{23}$$

where: θ_s – dimensionless temperature; $f_0 = \frac{\sigma\tau}{R}$ – dimensionless time - Fourier criterion; φ_1 – the first root of the characteristic equation to solve the differential equation of thermal conductivity under boundary conditions of the third kind; N_s – a factor that defines the shape

of the body; $e^{-\varphi_1^2 S}$ – a function that reflects the change in temperature over time; $\sin(\varphi_1 x)$ – function that reflects the change in temperature over the cross section of the sphere.

The characteristic equation for solving the differential equation of thermal conductivity under boundary conditions of the third kind is represented as:

$$BiI_{\frac{k-2}{2}}(\varphi_n) = \varphi_n I_{\frac{k}{2}}(\varphi_n), \tag{24}$$

where: I – Bessel function of the first kind.

The temperature in the center of thermal radiation (X = 0) and on the surface (X = 1) of the sphere for the regular mode is calculated:

$$\theta(0, f_0) = N_s e^{-\varphi_1^2 S}, \tag{25}$$
$$\theta(1, f_0) = P_s e^{-\varphi_1^2 S}, \tag{26}$$

where: $P_s = N_s \frac{\sin(\varphi_1)}{\varphi_1}$, (values P_s, N_s, φ_1, φ_1^2=$f(Bi)$ are reference [11, 12]).

Therefore, the presented method of algebraic transformation allows, under given boundary conditions of the third kind, to determine heat transfer coefficients on the surfaces of the sphere, namely: α_1 - from the internal volume of the sphere with a constant temperature Tcp1 to the wall surface, taking into account all types of heat exchange, α_2 - from the external surface of the wall to the environment with a constant temperature T_{en2} , as well as the temperature of the internal and external media, respectively T_{en1} , T_{en2} ($T_{en1} > T_{en2}$). The coefficients α_1 , α_2 will be constant in time, and the temperatures T_{en1}, T_{en2} constant in both time and surfaces [11-14].

In the steady state heat transfer mode, the total heat flux Q transferred through the uniform spherical wall from the higher temperature medium to the cold medium will be constant for all isothermal surfaces and is defined as:

$$Q = \frac{4\pi(T_{en1} - T_{en2})}{\frac{1}{\alpha_1 r_1^2} + \frac{1}{\mu}\left(\frac{1}{r_1 + r_2}\right) + \frac{1}{\alpha_2 r_2^2}}, \tag{27}$$

where: R_{sp} – thermal resistance of heat transfer to spherical wall, K/W, α – heat-transfer coefficient, W/(m^{2}K).

In equation (27), the $\Delta T_{en} = T_{en1} - T_{en2}$ is the total temperature head, and the expression in the denominator is the heat transfer coefficient of the spherical wall K_{sp}, W/K:

$$K_{sp} = \frac{1}{\frac{1}{\alpha_1 r_1^2} + \frac{1}{\mu}\left(\frac{1}{r_1 + r_2}\right) + \frac{1}{\alpha_2 r_2^2}}. \tag{28}$$

The $R_{sp} = 1/K_{sp}$ value is the thermal resistance of the heat transfer of the spherical wall:

$$R_{sp} = \frac{1}{\alpha_1 r_1^2} + \frac{1}{\mu}\left(\frac{1}{r_1 + r_2}\right) + \frac{1}{\alpha_2 r_2^2}. \tag{29}$$

For the case of a multilayer sphere:

$$R_{sp} = \frac{1}{\alpha_1 r_1^2} + \sum_{i=1}^{n} \frac{1}{\mu_i}\left(\frac{1}{r_i + r_{i+1}}\right) + \frac{1}{\alpha_2 r_{n+1}^2}. \tag{30}$$

Heat flow through a single-layer ball wall under the condition d = 2r:

$$Q = \frac{\pi(T_{en1}-T_{en2})}{\frac{1}{\alpha_1 d_1^2}+\frac{1}{2\mu}\left(\frac{1}{d_1+d_2}\right)+\frac{1}{\alpha_2 d_2^2}} = K_{sp}\pi(T_{en1} - T_{en2}). \quad (31)$$

In determining the heat transfer through the single-layer spherical wall, the temperatures at the wall boundaries Ts_1 and Ts_2 are unknown. To calculate unknown temperatures, a heat exchange section is taken in such a way that at one of its borders there is a known temperature, and at the other - the desired one. That is, the temperature Ts_1 should be used to calculate the temperature T_{en1} , and the cold ambient temperature Ten_2 [9, 13] should be used to calculate the temperature Ts_2. It follows that the temperature on the inner surface of the sphere will be written by the equation of the form:

$$T_{s1} = T_{en1} - \frac{Q}{4\pi\alpha_1 r_1^2}, \quad (32)$$

and the temperature on the outer surface of the sphere - by the equation:

$$T_{s2} = T_{en2} + \frac{Q}{4\pi\alpha_2 r_2^2}. \quad (33)$$

It is known that the question of redistribution of thermal energy through the enclosing surface of a spherical shape for stationary and non-stationary heat exchange modes involves in both cases the analysis of the differential equation of thermal conductivity, namely Fourier's law. However, for a non-stationary mode, it is necessary to take into account the multifactoriness of the described process, namely the setting of initial conditions, since the temperature field T (x,τ) changes both in space and in time. In turn, the stationary mode is characterized by the univariability of the initial temperature field, since temperature is in this case a function of only one variable - the radius r (T = T (r)), and given constant physical coefficients under boundary conditions of the third kind, which fundamentally assumes an accurate analytical solution of the differential equation of thermal conductivity (heat losses). Thus, the formalization of the stationary regime will make it possible to calculate heat losses for the specified burial levels of spherical and parallelepiped structures, as well as establish temperature minima of bearing soils to ensure optimal temperature and humidity inside fruit and vegetable storages.

Given the expressions (28) and (29), the heat flux equation (27) through the spherical surface will take the general form:

$$Q = \frac{4\pi\Delta T_{en}}{R_{sp}}. \quad (34)$$

That is, during heat transfer through the ball wall, the temperature differences in the heat exchange sections are directly proportional to the thermal resistances of these sections [15].

Heat flow through the flat enclosing surface [11, 15]:

$$Q = \frac{T_{en1}-T_{en2}}{\frac{1}{\alpha_1}+\frac{b}{\mu}+\frac{1}{\alpha_2}} S, \quad (35)$$

where: b - wall thickness, m; S - heat exchange surface area, m^2 .

Analysis of expressions (34) and (35) showed that thermal losses through the spherical surface of the buried fruit and vegetable storage will be less than through the flat surface, due to the geometric limitation of the contact area, which is the design specificity of the energy

efficiency of the spherical structure. The use of formulas (33) and (34) in the calculations will make it possible to assess the temperature difference inside the fruit and vegetable storage in accordance with the temperature dynamics of the soil subjected to target cooling for various operational ranges.

3 Discussion of results

Mathematical processing of the results of the study of thermal losses of buried vegetable storages was carried out on the basis of Excel software with fixed thermal technical characteristics of the enclosing structures, soil and the initial temperature distribution in the bearing mass. Comparative calculations on the criterion of heat losses through the enclosing surface of buried storages showed a significant superiority of spherical structures over typical storages - with parallelepipedic geometry of the internal space (Fig. 3)

Reinforced concrete with density of 2500 kg/m^3 with constant thermal conductivity coefficient of μ = 1.92 V/mK, which has good thermal insulation properties and heat transfer coefficient lower than, for example, metals, is accepted as a model material for tested enclosing structures of both spherical premises and premises with flat enclosing surfaces. The thickness of the walls of both types of rooms was included in the design algorithm is the same - equal to 0.4 m. The diameter of the outer and outer walls of the spherical room are respectively d = 10 m and d = 9.2 m. With the same volume of rooms - 407.5 m^3 , calculations showed that isothermal surfaces between which heat transfer occurred at flat fences had a much larger area. Since the heat transfer coefficients α_1 and α_2 are complex values, taking into account the simultaneous transfer of heat by convection and radiation, since they are included in the calculated algorithm according to the average values. As an additional condition, the calculations do not take into account the heat transfer coefficient of the external surface of the enclosing structures, due to the significant external thermal resistance of the specified soil mass.

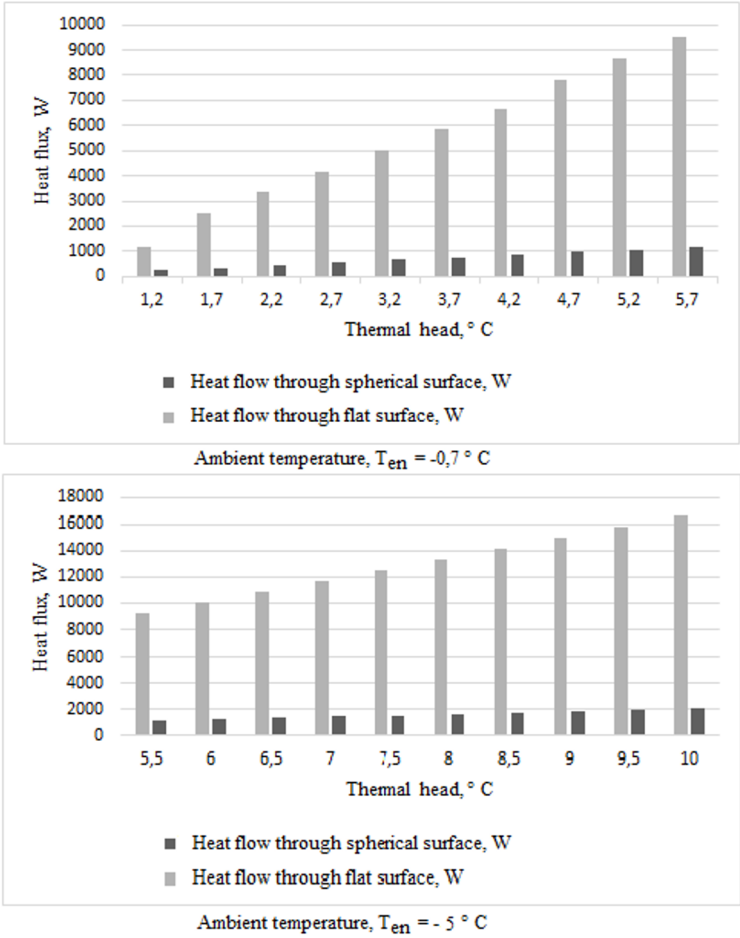

Fig. 3. Dependence of heat losses Q on total temperature head ΔT_{en}

It is known that temperature fluctuations in the soil layers lag in time relative to fluctuations in the outside air temperature, therefore, at the maximum freezing depth, negative temperatures in the soil are recorded much later than the coldest period of the year. Taking into account the perspective and availability of bearing soils as sources of low-potential thermal energy for structures of the production sector with controlled temperature modes, it is possible, using the target cooling system of the contact mass, to set the regulatory and technological values of the temperature of the cooling medium. For example, by means of a technical solution based on the Kayete principle, the carrier soil mass is treated with pre-compressed to several MPa air when it is supplied from a constant volume tank during the expansion stage. The physical and technical effect of cooling in this way may well provide a state of "freezing" or even freezing of soil particles [16, 17, 18].

In modern conditions, the electricity generated to generate cold varies significantly in cost for day and night consumption (one night kilowatt per hour can be 1.5... 2 times cheaper than day). Here it is also necessary to mention seasonal temperature fluctuations, and in the same aspect to touch upon the topic of climatic dynamics on the planet. All these are prerequisites for intensive research and rational operation of thermal storage properties of bearing soil massifs. The issue of using cold-charged soils technologically and on the basis of the "theory of enthalpy difference" is associated with the solution of design problems related to the

creation of modern energy-saving microclimatic zones and structures for storing agricultural products, including placement in underground horizons [18, 19, 20, 21].

Testing of the proposed algorithm of computational procedures can be carried out on the basis of the calculation of the temperature T_{en2} of the cooled soil required to obtain the technological temperature T_{en1} inside the spherical storage in the operating range from $+1^0$ C to $+5^0$ C. At the same time, it is taken into account that thermal power with volumetric density is evenly distinguished throughout the volume and creates heat flow through the surface of the sphere at the maximum temperature difference between internal and external media. The obtained results, visualized in the graphs (Fig. 4), give a clear idea of the principle of temperature distribution of the center of the spherical storage T (r) depending on the steady-state temperature on its surface or near it T_{s2}. It should be added that, in the steady state, the temperature inside the spherical-shaped room ceases to depend on the time, respectively, the amount of heat (heat flux) that is released per unit time inside the spherical surface will be equal to the amount of heat passing per unit time through the surface.

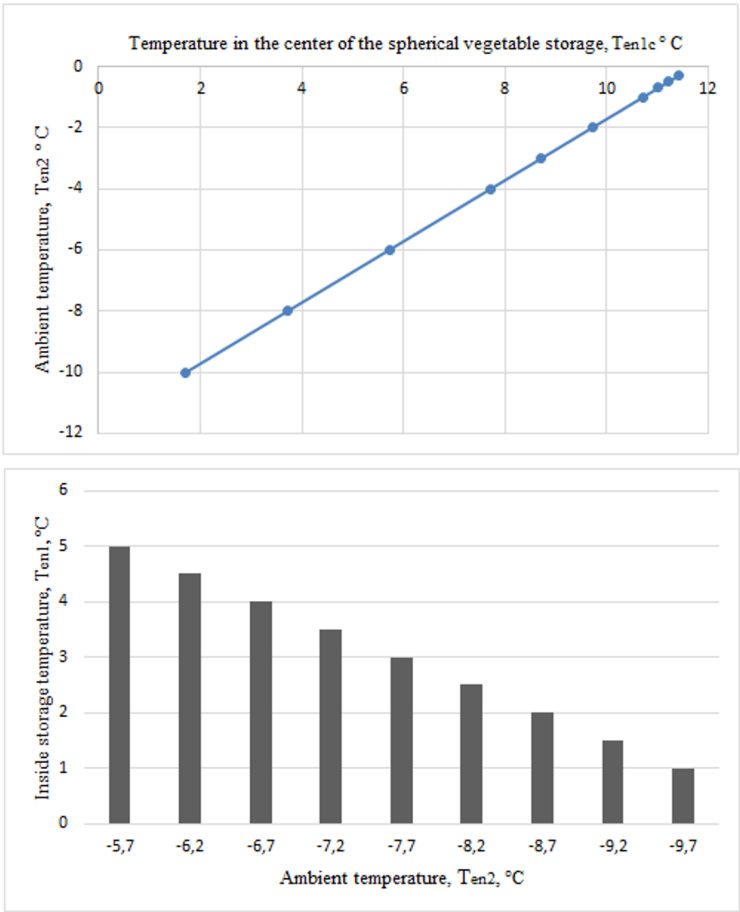

Fig. 4. Dependence of temperature inside and center of spherical fruit and vegetable storage tank T_{en1} on temperature of cold-charged soil T_{en2}

4 Conclusions

Thus, the study of the feasibility of developing buried storages shows the prospect of using a spherical shape of architectural solutions for premises for long-term storage of agricultural products. This is primarily due to the need for energy-efficient and promptly available storage capacities of fruit and vegetable enterprises of small forms of management in the agro-industrial complex of the Russian Federation. The possibility of implementing such technological solutions is confirmed by the historical experience of technical innovation at the level of laboratory-practical tests of functional devices for obtaining low temperatures, the physical and technical process of which is based on the Kayete principle. In turn, it is necessary to solve the issue of developing methods for cooling the support soil massif surrounding and contacting the surface of the buried storage, which is a mandatory element of the operation of bearing soils, the functional value of which is determined by the cold storage capacity and the duration of the heat exchange period taking into account the external positive ambient temperatures. In addition, the proposed prospect of developing capacities for storing fruits and vegetables suggests, in addition to realizing the physical effect of cold production according to Kayeta, "capturing" and accumulating a climatic negative resource in winter, which allows us to talk not only about the high efficiency of this technology, but also categorize it as energy-saving. The methodological fragments of the formalization of enthalpy theory presented for testing, in relation to the temperature dynamics of soil masses, are the basis for algorithming the analytical forecast of the temperature regime: at a given point in the internal space of the storage in operation - at each particular moment of time - in a given underground horizon of the reference soil.

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