Thermal stabilization of buried storage facilities based on air compression as an alternative refrigerant

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Abstract. At the present stage, vegetable growing is one of the promising areas of crop production development due to the consistently high year-round demand for fresh vegetables and their processed products. In this regard, it is necessary to pay special attention to measures for post-harvest refinement of the crop, extending the period of its sale and processing, which requires the creation of appropriate storage conditions. The publication discusses the prerequisites and specifics of designing technological systems for small businesses based on the development of deep-seated spherical vegetable storages operating using alternative energy sources.

1 Introduction

Today, vegetable growing is one of the promising areas of crop production development due to the consistently high year-round demand for fresh vegetables and their processed products, but at the same time one of the most labor-intensive and capital-intensive branches of agriculture. The high dependence on climatic conditions, the perishable nature of the grown products significantly complicate the production processes, as well as the storage technology and the conditions of its sale [1, 15]. At the same time, the economic condition of the business entity, the form of management and sources of financial support play an important role in the implemented technological program. This makes it possible to formulate a priori a hypothesis on technical innovation in the aspect of modernization or comprehensive re-equipment of the material base, including fixed assets, adequately to the "ceiling" of investments in the developing business for each real commodity producer.

In the Russian Federation, according to the per capita consumption of vegetables and potatoes, approximately 111 kg/person of potatoes and approximately 80 kg/person of vegetables are required each year, which totals 27,886 thousand tons [2, 16].

Research shows that 1/3 of the year, i.e. actually four months a year, the population uses the harvest directly from the fields, which is more than 9,202 thousand tons of fresh vegetables and potatoes, but the problem of seasonal storage remains relevant even in this case. Currently, there are two main principles of storage – short-term, about 3 months and long–term - 9 months a year. The analysis of crop separation at the storage stage showed that

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short–term storage accounts for 25 % of the total shaft, and long-term storage – 42 %. Thus, in order to continuously provide the country's population with domestic fruit and vegetable products throughout the year, 67% of the harvest harvested from the fields must be stored, which is over 18,683 thousand tons.

Modern integrated capacities for one-time storage of fruits, vegetables and potatoes in the Russian Federation amount to 9918.4 thousand tons. But if we consider capacities that meet modern storage standards in terms of quantitative adequacy, then even a special fund intended exclusively for food fractions is not enough in volume for 8765 thousand tons. In turn, the farms of the Russian Federation provide the gross harvest of vegetables and potatoes is 32.4 million tons, fully meeting the needs of the population in this type of product. However, the remaining 23.2 million tons deposited shows that the harvest is about 13.3 million tons, that is, more than 57 %, there is nowhere to store in Russia [3, 4, 17].

Nevertheless, the increase in gross collections of fruits and vegetables continues, and the sale of these products should be carried out at an optimal price. In this regard, it is necessary to pay special attention to measures for post-harvest refinement of the crop: extending the period of its sale and processing, and this requires the creation of appropriate storage conditions, under which the resulting products will be highly profitable and competitive.

The movement of the Russian agro-industrial complex towards the dominant indicators of trade and the economy of the world arena should not be hindered by technological backwardness in the construction of agricultural facilities. However, despite the widespread construction of new and modernization of functionally outdated storages, most small businesses cannot demonstrate the availability of modern vegetable storage facilities equipped with a cold-generating automated kit and a high-quality ventilation system due to their high market value. In addition, the issues of energy-efficient and environmentally safe production of low temperatures, as well as the issues of manufacturability of transportation and accumulation of cold remain unresolved to the end.

Special attention, in this case, should be attracted to a non-standard project of a deep-type spherical vegetable storehouse, the implementation of which assumes, on the basis of channeling low-potential heat to an array of bearing soil, the creation of an optimal temperature regime for storing products with a guarantee of its quality for a long period of time (Figure 1) [5, 6, 7].

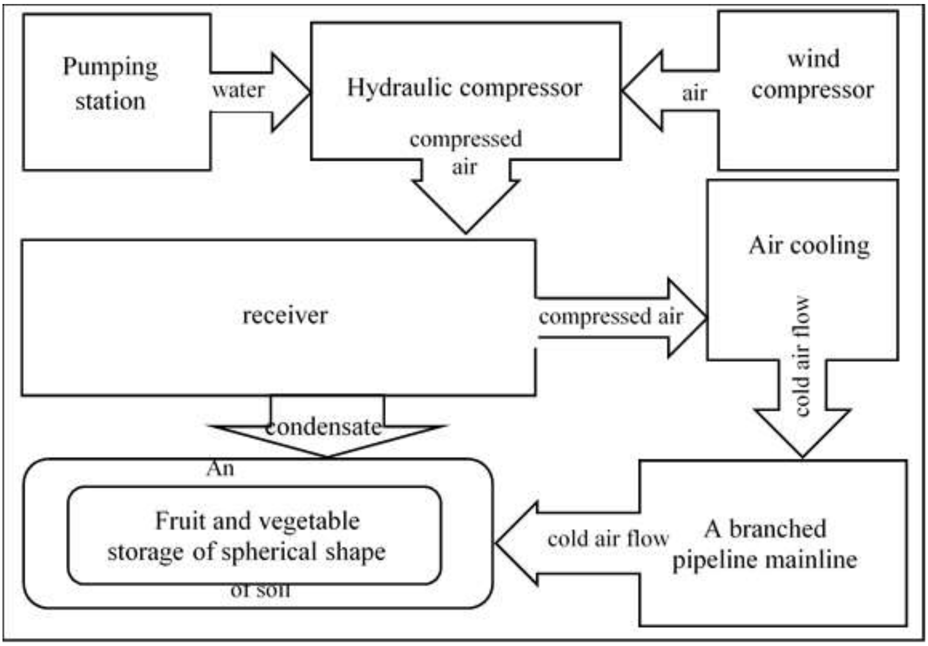

Fig. 1. The scheme of the technological system of generation, transportation and accumulation of low-potential heat.

The purpose of the proposed technical solution is to reduce the cost and environmentally protect the air cooling method for "charging" the accumulating soil mass with cold channeled to it. The use of air as a cooling agent is a modern and effective method of combined cooling, and cooling the air itself when expanding it from a constant volume is the physical effect that can be realized if a power plant is used like a single–stage reciprocating compressor.

The only question is that often additional energy-consuming equipment is not appropriate for implementation, subject to financial constraints within an already functioning technological system. Therefore, in order to achieve this goal, a project of "parallel functionality" is needed, that is, the use of the hidden potential of fragments of technical systems implementing specified processes that are not purposefully related to the intended innovation. In this regard, a power plant was designed using the injection principle of compressing air with water in storage tanks operating in a cyclic change of filling them from the well to a predetermined level, as a result of which air is supplied to the receiver by pressure (0.6-0.7 MPa). At the same time, the basic function of the hydraulic structure – the distribution and supply of water to technological facilities – is not violated.

It should be noted that the physico-technical process of compressed air production, from the point of view of energy efficiency, is unprofitable, since due to significant losses during transportation from the compressed air source, the compressor, to the end user, its cost increases to a level 50 times higher than the price of fossil fuels and 15 times higher than the price of electricity. That is, in fact, at the end point of compressed air consumption, only 15% of the consumed electricity is used for its further expansion, and most (about 85%) is the heat generated by the compressor during operation. For the proposed installation, the operational energy efficiency level is 40-50% [8].

Global warming of the climate on the planet has contributed to the development of strict recommendations and requirements for refrigerants of the fourth generation – hydrofluorocarbons R-134a, R-152a, R-125, R-32, etc. At the same time, a refrigerant with excellent thermodynamic characteristics, high chemical stability and good physical properties has not yet been found. At the same time, it must be in an affordable price range and fully meet all the requirements of environmental standards [9.10].

Experimental practice shows that refrigeration equipment can work efficiently and without causing damage to the environment if natural refrigerants are used in it. The point is that the cost–effective operation of an alternative natural refrigerant, air, should be an economic prerequisite for the creation of energy-efficient and resource-saving technological complexes that ensure the creation of optimal all-season temperature regimes for the storage of agricultural products. The combination of manufacturability of technical solutions for the production and transportation of compressed air, as well as high transmitted power with object dimensioning with the implementation of the refrigerant function makes it possible to consider pneumatic systems as sources of an inexhaustible energy resource. However, there are a number of reasons why air as a refrigerant has not become widespread: low specific heat capacity (approximately 1 kJ / kg · K), low cooling capacity of compressor-type installations (no more than 100 kW) with inadequate high cost of their production and high-tech requirements for components, and, most importantly, profitability as an indicator of the feasibility of development This direction becomes important only if the required productive temperature does not exceed (minus 50 °C). It should be added that in order to obtain such temperatures, the compressor unit has to be operated on large volumes of air, but the compressor is the main energy consumer in refrigeration systems (about 90% of the total capacity) [4, 11]. That is, to improve operational manufacturability, an innovative technical solution with a fundamentally new approach to compression is needed.

The above-mentioned deep-type vegetable storage project as a technical solution is a functional fragment of a technological system that integrates its structuring method: a method for the optimal selection of environmentally friendly natural refrigerants, algorithmization of the calculation of compressed air pressure for the cycle of a single-stage piston-type power plant with direct supply of refrigerant to an extensive network of air ducts and structural synthesis of technological objects, both according to their internal target function and according to the general functional and technological contour.

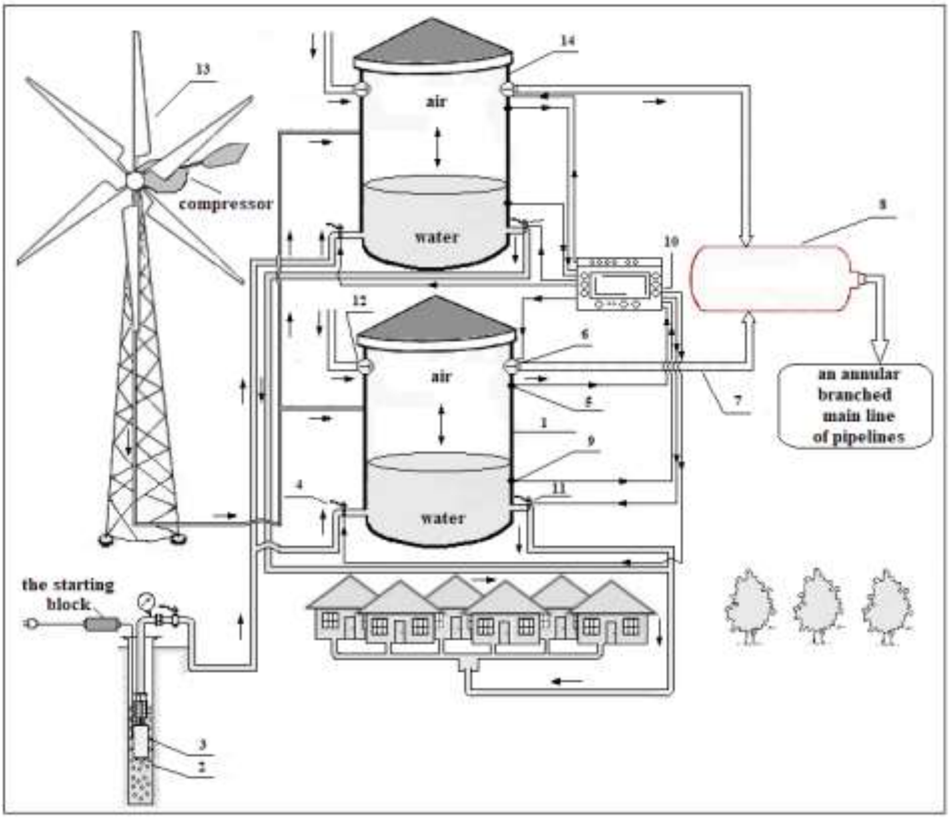

Fig. 2. Schematic diagram of a synthesized hydraulic compressor unit.

An example of structural synthesis based on the use of the latent potential – in this case – of a water distribution system is a designed hydraulic compressor unit (Figure 2), which implements air compression by compressing it in the upper part of the tank 1 with water pumped into it from a well 2 by an electric pump 3 through a water intake valve 4.

At the moment when the air pressure in the surface space of the tank 1 reaches a set value controlled by the upper level sensor 5, which occurs when it is 85% full, the automatic control system opens the air shut-off valve 6 and compressed air enters the receiver 8 through the pipeline 7, from where, after cooling and condensation of water vapor, it is timely supplied to the branched the main pipeline to the cooled soil mass. Further, when water is taken from the tank 1 to technological facilities, its amount begins to decrease until the lower level sensor 9 is triggered, while the controller 10 synchronizes the operation of the valve system so that the water intake valve 4 is kept closed, the water distribution valve 11 is open for water to exit to technological facilities, the air intake valve 6 is closed and communication with the receiver 8 is missing, and the check valve 12, triggered by a pressure drop, passes atmospheric air into the surface space of the tank 1. In this state, the system will be held until the lower level sensor 9 gives a signal to close the water distribution valve 11. At the same time, the controller 10 opens the water intake valve 4 and the air intake valve 6. In the process of pumping water into the container 1, the check valve 12 will already be in a closed state, since there is no pressure drop from the moment filling the surface space with atmospheric air, further compression of which by a water mass will only seal the contact when the bypass opening is closed. Thus, the function of air compression is repeated adequately to the portion change of water in the storage tank 1, that is, the cyclicity of the process simulating the operation of a piston-type compressor unit is realized. Air compression can be intensified by forcibly pumping its additional volume into the surface space, both when the water level in tank 1 decreases and when it is filled. The theoretical model allows for the possibility of aggregating a design hydraulic structure with a wind compressor 13, since even with a regional minimum wind speed of 4 m/s, various modifications of wind turbines – including compact ones – are able to provide air supply of 1.5 m^3/h (0.025 m^3/s). Additionally, the capacity 14 can be used as a backup, operating according to the principle described above.

If we consider the proposed technical solution in the context of analyzing a business plan with the prospect of development into a technological system that guarantees a profitable flow according to the "harvest-product-commodity" scheme, first of all, attention should be paid to the reliable identification of the level of technical problems that determine in the technical solution the scope and depth of the theoretical justification of the possibility of technical implementation of the project hypothesis itself. What is it about ...: since compression is positioned as the main goal, therefore, the production of compressed air at high pressure in the required amount and stabilization of its flow regime will be the determining prerequisites for the formation of the algorithm of theoretical analysis. In this case, with the well–known fact of the "non–compressibility" of water - with an increase in pressure to 100 atmospheres, the density of water increases by only 0.5 % -design procedures can only be carried out for hydraulic structures with technologically sufficient pressure, but not exceeding 0.6-0.7 MPa. As experiments have shown, this pressure fully provides air compression for use in the cooling process and further supply to the branched pipeline line to the cold storage soil. Moreover, as practice shows, after the cooling process to ambient temperature, the air compressed within 0.4-0.5 MPa, with a sharp pressure drop to 0.1 MPa, which corresponds to atmospheric pressure, realizes a temperature of minus 70 °C.

Compressing the air with water has its advantage. Simultaneously with compression, it cools. The operated storage tank actually plays the role of a heat exchanger, where the initial decrease in air temperature occurs before further pumping it into the receiver. When air is compressed, its specific volume changes significantly, so to obtain 1 m^3 of compressed air at a design pressure of 0.7 MPa, 7.7 m^3 of atmospheric air must be treated. However, field experiments have confirmed the manifestation of the effect of dissolution of compressed air in water up to complete, and then, with pressure relief, intensive foaming of the aerated liquid. The solution to this problem is also possible through an experiment, but already mathematically – through the optimization of air exchange by portion volumes of a design hydraulic structure with virtual functionality and simulated atmospheric environmental conditions. At the same time, the model should take into account that water vapor also contracts, and condenses with a gradual decrease in temperature. Moisture from the air can be released both in volume, in the form of fog, and on the surface of the mirror of the compressing liquid, the temperature of which is lower than the dew point temperature. The model calculation of air exchange in the design technical solution assumed technological compression of air to a pressure of 0.7 MPa, at which the dew point is plus 3 °C. But this analytical block is not the final one either… The prolonged technical analysis showed the need for parametric integration of the function of regulating air exchange and the function of cleaning organized air flows from foreign inclusions. Condensed water captures and transfers all kinds of pollution, which, despite the installed filters, are still present in the air. Moisture falling out of the compressed air absorbs pollution, and the resulting aggressive mixture corrodes pipes and equipment parts. In addition, moisture falling out in the form of frost during air transportation through an annular branched pipeline line will create additional hydraulic resistance in it, eventually leading to blockages.

2 Research methodology

In connection with the above, the priority object of theoretical research of the proposed technical solution should be considered the process of air compression being implemented from the point of view of substantiating the possibility of its functional manifestation in an executive technical structure simulating a mechanical compressor unit with an electric drive.

As is known, for parametric analysis of compressor-type installations, it is necessary to have information about the full composition of the operated gas, its chemical formula, and a characteristic of each component, up to molecular weight and boiling point. Nevertheless, the implementation of analytical procedures to optimize the basic parameters of the gas is formalized by means of the "equation of state of an ideal gas" Under normal conditions, the air also obeys the law described by this equation:

$$P \cdot V_{\mu} = R \cdot T \tag{1}$$

where P – pressure, Pa; V_{μ} – molar volume, m^3; R – universal gas constant, J/MOL K; T – temperature, K.

Since air is a real gas, the computational algorithmization was carried out taking into account its "compressibility" – Z, used in thermodynamics to explain the deviation of the thermodynamic properties of real gases from the properties of ideal gases:

$$P \cdot V\mu = Z \cdot R \cdot T \tag{2}$$

The value of "Z" – the functional dependence of the composition of the gas, its pressure and temperature – was determined with the required accuracy according to the law of corresponding states:

$$Z = fn(PR, TR) = fn([P/PC],[T/TC]) \tag{3}$$

Using ready-made general tables of gas compressibility, freely available in various sources, based on the ratio of actual and critical values of temperature and pressure, the compressibility factor Z can be calculated using a computer for pure gases or their mixtures (for example, air).

Since the compression process can be both isothermal and often occurs with a change in temperature, the value of the compressibility coefficient will vary slightly. For the isothermal process T = const, an isothermal compressibility factor is introduced, which is calculated using the formula:

$$Z = -\frac{1}{V}\left(\frac{\delta V}{\delta T}\right) \tag{4}$$

However, in most cases, for air (at different pressures and temperatures), the compressibility factor differs from one by thousandths, which can be negligible. Only at pressures approaching 300 atm does it begin to increase and approach 1.1.

In practice, the most commonly used equations for evaluating compressor performance are the Soave–Redlich-Kwong, Peng-Robinson equations of state, Benedict-Webb-Rubin, Starling-Khan equations, API methods and others.

As a first approximation, for a given volume, including the volume of the cylindrical and conical parts, the calculation of compressed air pressure was carried out taking into account the design height of the container H = 7.5 m and its diameter D = 6 m. The air pressure when entering the compressor unit will always be equal to atmospheric P_0 = 10^5 Pa. The technological specifics are such that with a gradual rise in the water level, temperature changes do not occur, that is, the process of changing pressure and volume is isothermal. The air mass m remains unchanged. The compressibility factor Z is assumed to be equal to one. Then according to the Boyle-Marriott law:

$$P_0 \cdot V_0 = P \cdot V \quad (5)$$

where P_0 – atmospheric pressure, Pa; V_0 – initial volume, m^3; P – compressed air pressure, Pa; V – the volume of compressed air, m^3.

The volume of the cylindrical part of the container $V_с$:

$$V_с = \frac{\pi D^2}{4} H \quad (6)$$

where H – height of the cylindrical part of the container, m; D – the diameter of the base of the container, m.

The volume of the conical part of the container $V_к$:

$$V_к = \frac{1}{3}\pi R^2 h \quad (7)$$

where R – radius of the cone base, m; h – the height of the conical part of the container, m.

3 Discussion of results

In this case, it is easy to establish the volume of the container, which is 202.7 m3, and the pressure of compressed air – according to formula (5) it will be in the range of 0.6-0.7 MPa when filling the container with water by 85%. Figure 3 shows the functional dependence of compressed air on filling tank 1 with water in percentage terms. But it is fundamentally important that the compressed air pressure function can be reasoned according to any parametric characteristics of the water storage tank, that is, it is possible to size the hydraulic structure in accordance with the workspace of the technological facility. At the same time, the compression parameters will be fully adequate to the design mode of air cooling and its supply to the branched air main. Depending on the technological configuration scheme of the proposed compressor unit, the argument of this function may include a parameter for quantitative cyclic synchronization of operated water storage tanks.

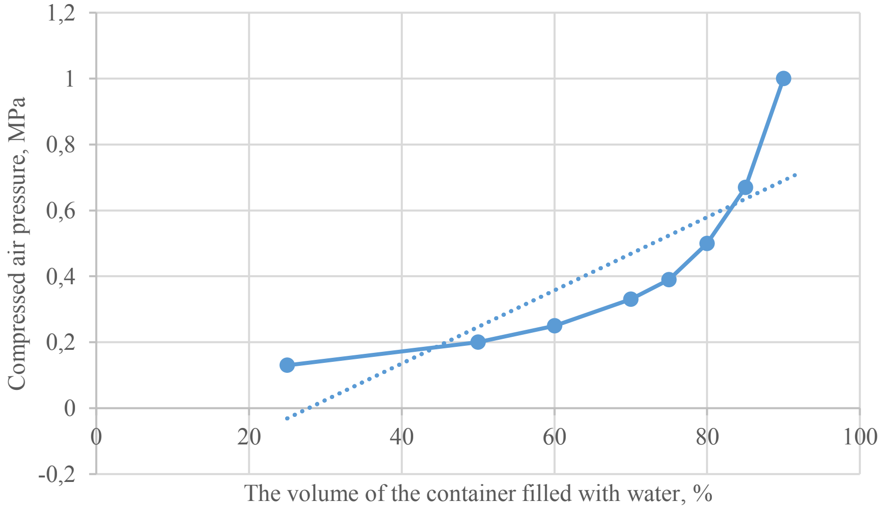

Fig. 3. Dependence of compressed air pressure on the volume of a container filled with water.

However, its aggressiveness to ice–ground fencing and insufficiently low crystallization temperature bring to the fore an alternative option – air - an inexhaustible environmental resource. Its expansion from a constant volume, known in the historical practice of technical innovation as the Cayete effect, which in modern conditions is a cardinal solution to a number of urgent tasks, both in terms of energy and resource conservation, and in optimizing the planning of technological facilities in real agricultural production.

As is known, the main reason for cooling a gas during its expansion without heat transfer is the energy cost of the expansion itself. Therefore, when developing the schematic diagram of a compressor unit with a hydraulic compressor, its functionality was based on the process of adiabatic expansion of compressed gas, which is accompanied by a decrease in temperature. The relationship between pressure and temperature for an ideal gas in an adiabatic process is described by the classical expression:

$$\mathrm{P}^{\gamma-1}\mathrm{T}^{\gamma} = const \quad (8)$$

Or

$$T2/T1 = (\mathrm{P}_2/\mathrm{P}_1)^{\gamma-1/\gamma})/k \quad (9)$$

where P_1 and P_2 – initial and final pressure, Pa; T_1 and T_2 – initial and final temperatures, K; γ – Poisson's ratio.

Since air consists of 99% diatomic oxygen and nitrogen molecules, its adiabatic index γ is very close to the value of 1.4, which is confirmed by the experimental determination of this value. For the technological implementation of soil freezing, an important parametric premise is that air compressed to 0.7 MPa at t = 20 ° C, adiabatically expanding to 0.1 MPa at γ = 1.4, creates a temperature field of at least 169 K. Or, if converted to degrees Celsius – minus 104.15 °C, which is close enough to the boiling point of liquid nitrogen minus 195.8 °C, also used as a refrigerant for freezing soils [12, 13, 14].

4 Conclusions

Thus, the following conclusion can be drawn, which in essence represents a balanced trinity: economic prerequisites clearly orient the vector of innovation towards local technologies using an alternative natural resource – the creation of technological systems of the type "production –processing – storage" based on small businesses (the maximum amount of state support to categories of small businesses for 2024 it ranges from 7 to 70 million rubles.); the functional structure of the technological system, integrated into a complex of demanded technical functions, involves the creation and accelerated development of design solutions aimed primarily at obtaining a highly profitable process for the production of low-temperature air flows and their transportation to objects of warehousing, processing and storage of fruits and vegetables (the optimal storage mode is near zero temperature (± 1 ° C) with relative humidity of the air is 90 – 95%); the technical implementation of physical operations is always based on a project for the implementation of the physical principle of operation – in this case, the hydraulic compression of air with its subsequent expansion from a constant volume, which, with an adequate flow rate in an adiabatic process, leads to a decrease in the temperature of the air flow passing from the receiver into the pipelines of the ring branched main. The theoretical foundations laid are consistent with the principles (laws) of thermodynamics, which makes it reliable to carry out a methodological adaptation of the physico-technical effect – here we can talk about the Cayette effect as the closest manifestation – when air performs work only at the expense of its internal energy, which is completely kinetic. That is why its sharp expansion leads to a decrease in temperature. The applied interpretation of the methodological base of functional structures research will not only improve the operational manufacturability of specialized equipment, but also synthesize highly efficient resource-saving technological systems already at the design stage with a guaranteed economic effect of 30-40%.

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