Modernization of the heat pump installation for drying wheat

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Abstract. The most energy-consuming and most critical stage of post-harvest processing is grain drying. Safety of grain depends on its drying. For drying grain, grain drying plants are used that remove excess moisture from the grain. In most cases, drying occurs under the influence of elevated temperatures with a constant supply of heat. After drying, the grain must be cooled to eliminate irreversible processes. The drying process is slow due to temperature limitations. To speed up the drying process, various techniques are used, one of which is the alternation of heating and cooling processes (differentiation of heat input). To increase the drying energy efficiency in the conditions of differentiation of the supply of thermal energy, it is advisable to use heat pump units. Heat pump units allow the creation of a heating agent (heated air) and a cooling agent (cooled air). Studies have shown that for different grain parameters, different temperature characteristics of heating and cooling agents are required. For independent temperature control of heating and cooling agents, an original design of a heat pump installation has been developed. To automate the control of the drying process, several control schemes have been developed and investigated.

1. Introduction

Nowadays, the food industry is the most problematic area of production, which is associated with the increasing consumption of food products of the world's population. The whole food industry is based on the capabilities of the agricultural sector [1, 2].

The agro-industrial complex (Agribusiness) unites all sectors of the economy involved in the production of agricultural products, their processing and bringing them to the consumer [1, 2].

Agriculture is the largest branch of the Agribusiness, which includes closely related crops and livestock, which account for 56% and 44% of agricultural products, respectively [1, 2].

More than half of all sown area is allocated for grain cultivation in Russia [1, 2].

One of the most important stages in the production of grain crops is post-harvest processing and drying of grain, which reaches 75 ... 80% of the total cost in terms of energy consumption [1-4].

The quality of the final material depends on the choice of grain drying technology, to which certain requirements are set forth in the technical regulation "On grain safety". In the technical regulation, an indicator is added, which is absent in the previous regulatory documents, of the content of benz(a)pyrene with a maximum concentration of 1 mg/kg, while the initial content of this substance on the surface of the grain is 0.25-0.53 mg/kg [5].

The quantity and quality of grain determines the availability of raw materials in many sectors of the food industry, in particular, milling, cereals and animal feed. Therefore, the elevator farm should carry out reception and continuous post-harvest processing of grain and ensure its full safety in a short time. Drying is the most important link in the production of complex mechanized lines for receiving and post-harvest grain processing. The predominant weight of harvested grain enters usually with high humidity, reaching up to 35%, and the safety of the grain depends on the operation grain drying plants.
Processes for drying grain processing businesses are characterized by significant power consumption. The proportion of physically and morally obsolete low-productivity drying equipment is high, which leads not only to an overspending of fuel and energy resources, but also affects the quality of products. About 55% of heat is spent on the implementation of technological thermal processes, so one of the main ways to increase the efficiency of heat use is to improve the technology. Improving the technology is directly related to an increase in equipment productivity, which, in turn, leads to an intensification of heat transfer and a decrease in specific heat consumption. Significant opportunities for saving resources are created during the automation of technological processes of drying grain crops. However, this promising way to optimize the control of drying processes in the processing sectors of the Agrobusiness has not yet found a worthy place in solving urgent problems of energy conservation [1-4].

The insufficiently high organization of post-harvest grain processing leads to crop losses of up to 20%. In turn, this affects the harvesting of high quality wheat, suitable for baking flour. In modern conditions of increasing energy consumption, on the one hand, and the shortage of energy resources, on the other hand, the issues of rational use of energy, utilization and recovery of heat in all processes of food technology are becoming increasingly acute. This also applies to grain drying, which is inevitably accompanied by incomplete use of coolant energy. In the drying technique, heat pumps are widely used, which make it possible to bring grain drying plants to high energy excellence regarding the use, utilization, and recovery of the heat of the spent drying agent. At the same time, energy costs are significantly reduced (up to 30%), and the implementation of the “soft” drying regimes with a drying agent with low moisture content due to its drying in the evaporator allows obtaining dried grain of high quality. The current level of development of computer technology, as well as advances in the theory of heat transfer and mass transfer during drying of colloidal capillary-porous materials, allow us to study the drying process of wheat grain in a closed cycle using a drying agent with the most energy-efficient connection schemes for a heat pump installation (HPI). In heat transfer systems, it is possible to use special dehumidifiers of compressed air, which can reduce the humidity of the coolant supplied to the grain and thereby speed up the process. Such systems can be equipped with air coolers designed to cool dried grain. Therefore, the urgent task is to develop a complex of mathematical models of a closed drying technological system for modeling simultaneously occurring heat and mass transfer processes: grain drying, drainage of the spent drying agent, regeneration of the working surfaces of heat exchangers, recuperative heat transfer between heat carriers of different temperature potential. It seems that it is precisely this direction that will create new energy-saving technologies and methods for drying grain in direct-flow mine grain dryers [1-4].

The principles of energy saving in the drying processes to date are clearly defined. The main ones include: maximum use of the heat of the spent drying agent due to its recycling; the use of heat pumps for low-temperature drying; use of secondary energy resources; mathematical modeling, providing the maximum degree of kinetic, hydrodynamic and thermodynamic correspondence; optimization and control of drying and heat treatment processes, preventing the loss of heat and electricity. Despite the established principles of energy saving in the drying processes, there is no single solution to their implementation. Therefore, solving energy-saving problems with a specific energy supply method requires an individual approach, taking into account the specifics of each type of product.

We are faced with the following tasks: presentation of the main characteristics of grain as an object of drying; description of air and drying agent parameters; identification of the ratio of the parameters of the designed drying process to experimental data; assessment of the energy efficiency of a shaft dryer using a heat pump.

In modern conditions of increasing energy consumption, on the one hand, and the shortage of energy resources, on the other hand, the issues of rational use of energy, utilization and recovery of heat in all processes of food technology are becoming increasingly acute. This also applies to grain drying, which is inevitably accompanied by incomplete use of coolant energy.

The most common source of thermal energy during the drying process is a liquid and gaseous fuel burner. When drying in this way, the hot combustion products are mixed with atmospheric air and fed into the drying chamber, so that the combustion products settle on the surface of the grain. In accordance with the regulation "On grain safety" the use of this method is prohibited. To meet these
requirements, heat exchangers are used that transfer the thermal energy of the combustion products to the drying agent without mixing, while the specific energy consumption increases by 2-2.5 times [5].

Analysis results drying kinetics equations showed that most of the thermal energy consumed "in an empty" and to generate heat energy device have a low efficiency, which makes them uneconomical. The use of alternative sources of thermal energy can reduce the cost of drying the grain. The HPI installation can be used as such a device [3, 4].

The physics of the processes that occur during the operation of HPI allows you to create a drying agent and a cooling agent, redistributing thermal energy between air flows. In addition, during the operation of HPI, energy is expended only on the compression and transfer of the refrigerant, thus, the main characteristic of HPI is the heat recovery coefficient. The heat recovery coefficient shows how many units of thermal energy can be obtained at the cost of one unit of mechanical energy.

Theoretical conjectures allow us to conclude that in the process of drying grain, HPI can be used as a means of creating a drying agent and cooling agent [6].

To confirm the use of alternative sources of thermal energy, a grain dryer with a heat pump installation was collected and investigated.

The feasibility of using HPI in the drying process is theoretically substantiated and practically confirmed. The device of modern HPIS does not allow to achieve temperature adjustments (the main indicator of the drying process) in wide ranges, and therefore a new approach to HPI management is necessary - the development of a control system.

2. Main part

The grain drying process is based on the physical process of moisture transfer under the influence of the vapor pressure difference in the grain and the drying agent. Thus, the drying process proceeds when the vapor pressure in the grain is higher than the vapor pressure in the drying agent. To create such conditions, it is necessary to increase the temperature of the grain. To increase the temperature of the grain, several heating methods can be used: conductive; convective; microwave; radio emission; infrared. The most common and safest for grain is convective heating - heating the grain with heated air. Thus, to carry out the drying process, it is necessary to increase the temperature of the drying agent. During drying, part of the moisture evaporated from the grain passes into the drying agent, after which the drying agent is removed [1-3].

After the drying process is over, a prerequisite is the cooling of the grain, because with prolonged cooling or prolonged exposure to elevated temperatures (more than 40 °C), the grain can lose not only its viability, but also reduce its food and beverage qualities due to sintering of nutrients contained in the grain. The commodity-food qualities include germination energy, germination energy, gluten yield. In the absence of gluten, grain loses all technological value [1, 2].

When designing grain dryers, the main calculation is reduced to compiling a heat balance to determine the performance of the furnace devices.

In the classical form, the heat balance equation is as follows as in equation (1):

\[ Q = (Q_{hg} + Q_l + Q_{da})/h \]  

\( Q \), the heating capacity of the combustion device (the amount of energy produced per 1 second), MJ;  
\( Q_{hg} \), the amount of heat to heat the grain, MJ;  
\( Q_l \), heat loss through the walls of the grain dryer and technical holes due to convective flows, MJ;  
\( Q_{da} \), the amount of heat carried away by the spent drying agent environment, MJ;  
\( h \), the efficiency of the furnace device, %.

The amount of heat to heat the grain is determined as in equation (2):

\[ Q_{hg} = Gc(T_2 - T) \]  

\( G \), the weight of grain, kg;  
\( c \), is heat capacity of grain, J / (kg K);  
\( T_2 \), the temperature of heated grain, °C  
\( T \), the temperature of incoming grain (approximately equal to ambient temperature), °C.
The maximum temperature of heating grain during drying of seeds in the “soft” mode is about 45 °C, the maximum temperature of grain during drying is no more than 62 °C [7]. When the grain is heated, when drying is above the maximum permissible value, irreversible baking processes begin to occur in it, in other words, the grain begins to fry. In this regard, the installation of temperature limits is necessary.

The heat capacity of grain - the value is not constant and it depends on the moisture content of the grain and its chemical composition. In general terms, with some assumptions, the specific heat of grain is determined as in equation (3) [8, 9]:

$$c = 0.01(c_0(100 - w) + c_w w)$$

$c_0$, the specific heat of dry solids of grain (depending on chemical composition varies from 750 to 1760), kJ / (kg K);
$c_w$, the specific heat of water absorbed by the grain (has a standard value of $c_w = 4.19$), kJ / (kg K);
$w$, is grain moisture, %

In the post-harvest period, the moisture content of the grain reaches a value above 25% (up to 35%), thus, the heat capacity of the grain ranges from 480 kJ / (kg K) to 1500 kJ / (kg K).

In the period of post-harvest grain processing, the average ambient temperature in our region ranges from +15 °C to +25 °C. Thus, analyzing the equation of the amount of heat for heating grain, the consumption of thermal energy for heating 1 kg of grain in the drying chamber to 45 °C, which is a conditional value, ranges from 9.6 MJ to 45 MJ.

Heat losses through the walls of grain dryers and technical holes are currently minimized due to the use of modern heat-insulating materials with a heat transfer coefficient of not more than 2 J / (m2 K). Thus, heat losses are so small that they can be neglected.

To determine the amount of heat carried away by the spent drying agent, it is necessary to use the following equation (4):

$$Q_{da} = L(J_2 - J_0)$$

$L$, the weight of spent drying agent, kg;
$J_2, J_0$, is enthalpy of the spent drying agent and atmospheric air, respectively, kJ / kg.

Enthalpy depends on many factors, such as temperature, humidity, pressure, and is determined by the J-d diagram or by the Ramzin formula. During the drying process, the enthalpy of the spent drying agent ranges from 100 to 140 kJ / kg, and the enthalpy of atmospheric air during the drying period for our region is from 15 to 20 kJ / kg.

The mass of the spent drying agent is determined as in equation (5) [1, 2, 8, 9]:

$$L = 1000(B - w_2 T_0)/(622 w_2 T_4)$$

$B$, is drying agent pressure in the chamber, atmospheres;
$w_2$, the humidity of drying agent, %;
$T_0$, the temperature of spent drying agent, °C.

Substituting the restrictions on the values of the values, it can be seen that the mass of the spent drying agent ranges from 10 to 17 kg per 1 kg of grain with a decrease in grain moisture by 1%. Thus, the consumption of the drying agent is about 100-340 kg for drying 1 kg of grain, which approximately corresponds to the volume of 100-400 m³.

The drying agent carries away heat in an amount of from 8 to 42.5 MJ / kg.

Taking into account the efficiency of the furnace-heat exchanger system, not exceeding 12%, the heating capacity of the furnace for drying 1 kg of grain should be from 147 MJ to 730 MJ, while the share of the cost of thermal energy carried away with the spent drying agent is approximately 45-50%.

When the grain drying process is completed, it is cooled by atmospheric air, and there is practically no decrease in grain moisture because it cools slowly. The air flow rate for cooling 1 kg of grain is determined as in equation (6):

$$L_c = Gc(T_3 - T_2)/(J_1 - J_0)$$

$T_3$, the final temperature of grain sent for storage (approximately equal to ambient temperature), °C;
$J_3$, the enthalpy of air after grain cooling, kJ / kg.

The value of the final temperature is determined from the condition (as in equation (7)):

$$0 < T_3 < T + (5...10)$$ (7)

Since the temperature of the grain after cooling should not exceed the outside temperature by more than 5 ... 10 °C, however, this temperature should not be lower than 0 °C.

According to the results of the analysis, the main parameters of the device for creating a drying agent and a cooling agent were determined and reflected in the conclusion.

The grain drying process consists of three main stages: heating the grain, removing moisture from the grain, and cooling the grain.

A supply of thermal energy is required to heat the grain. Also, the process requires the supply of part of the thermal energy to remove moisture. The cooling process requires the selection of thermal energy from the grain. The total amount of thermal energy supplied to the grain should be taken from it. The selection of thermal energy is proposed to be carried out using a cooling agent - air having a low temperature in the range from 0 to 10 °C.

As a device for creating a drying agent and a cooling agent, a heat pump or a heat pump installation. HPI is ideally suited - a device for transferring thermal energy from a less heated source of energy to a more heated one due to the transition of the refrigerant to various aggregate states.

The main parameters of the device for creating a drying agent and a cooling agent are: initial and final temperatures of the drying and cooling agents; consumption of drying agent and cooling agent; heat output; cooling capacity; compressor power. To determine the main parameters of the device for creating a drying agent and a cooling agent, it is necessary to know the performance of the grain dryer, the time spent by the grain in the drying chamber and cooling chamber, and the initial and final moisture content of the grain.

In the period of post-harvest grain processing, the average ambient temperature is + 15 °C, and air humidity is about 75%, initial grain moisture is about 24% or more, final grain moisture is 14%, grain dryer productivity is 4 tons / hour.

In addition to these data, the maximum temperature of the drying agent for the initial moisture content of wheat grain of 24% or more is 60 °C, and the maximum temperature of the grain is 30 °C.

For heating 1 kg of grain, the specific heat consumption at an initial grain temperature of 15 °C is 24% humidity or more, a temperature of a drying agent of 60 °C and a humidity of a drying agent of 75% and a final grain temperature of 30 °C will be about 40 kJ / kg. With a grain dryer productivity of 1 kg / s, the heat consumption for heating the grain will be 40 kJ / s = 40 kW. The flow rate of the drying agent will be 0.91 kg / s.

It is necessary to spend 611 kJ / kg to reduce the moisture content of 1 kg of grain from 24% to 14% at a grain temperature of 30 °C and a temperature of a drying agent of 60 °C. Thus, the thermal power for the drying zone is 611 kW at a capacity of 1 kg / s. The consumption of the drying agent at its temperature equal to 60 °C is 2.4 kg / s.

For cooling the grain from 30 to 150°C, heat removal in the amount of 38 kJ / kg is necessary. With a grain dryer capacity of 1 kg / s, heat removal is 38 kJ / s = 38 kW. In this case, the flow rate of the cooling agent with a temperature of 50 °C is 2.3 kg / s.

Thus, the thermal power of the installation of creating a drying agent and a cooling agent should be 651 kW at an air flow rate of 3.31 kg / s, and the power of cold formation 38 kW at an air flow rate of 2.3 kg / s. As such a device, it is advisable to use HPI with a minimum heat output of 651 kW.

The choice of HPI is reduced to the determination of heat transfer areas, circuit temperatures, compressor capacity, brand of refrigerant, compressor power.

The conventional scheme of the HPI operation is presented in Figure 1. The HPI consists of an evaporator, condenser, inductor and compressor.
Figure 1. Scheme of the action of the heat pump installation. Legend: 1 – the capacitor; 2 – the throttle; 3 – the evaporator; 4 – the compressor; A - the contour of the creation of the drying agent; B - circuit of creating a cooling agent.

The heat transfer areas directly depend on the temperatures of the heat exchangers, the initial and final air temperatures. So for the contour of creating a drying agent, the minimum heat transfer area should be 22 square meters at a heat exchanger temperature above +90 °C. The area of the cooling circuit must be at least 8 square meters at a heat exchanger temperature of 0 °C.

To do this, it is necessary to use a refrigerant that would have a boiling point range from 0 to 100 °C. These requirements are met by R142b having a boiling point of 0 °C at a pressure of 0.29 MPa and a boiling point of 100 °C at a pressure of 1.73 MPa. Thus, the compressor must create a pressure difference of 1.44 MPa, and the daily mass of the pumped refrigerant is 2.1 kg / s. Under these conditions, the electric power of the compressor should be at least 164 kW with a grain dryer capacity of 1 kg / s.

When the capacity of the grain dryer is 1 ton / h or 1000 kg / 3600 s = 0.28 kg / s, which is 3.6 times less than in the considered version, all power values must be reduced. For a grain dryer with a capacity of 1 ton / h, it is necessary to use an HPI with an electric compressor power of \( P = 45.5 \text{ kW} \). For drying one ton of grain, the consumption of electric energy will be at least 45.5 kWh.

To confirm the parameters of the HPI, the assembly of the installation and research of the parameters in laboratory conditions were performed.

The results of the analysis of the equations of the heat balance of grain drying show that the specific heat power of the source of heat energy for drying 1 kg of grain, at a temperature and humidity of ambient air of 15-25 °C and 75%, respectively, ranges from 17.5-87.5 MJ / kg.

As sources of thermal energy in the convective drying method, mainly two technical devices are used: a burner of liquid or gaseous fuel; electric heating elements. The analysis showed that most modern furnace devices have an efficiency of not more than 12%, that is, their heat output should be 147-730 MJ / kg. Modern electric air heaters have an efficiency of about 95%, that is, their heat output should be 18.4-92 MJ / kg.

An alternative source of thermal energy for the creation of a drying agent can be a HPI or a “heat pump”.

Currently, heat pumps are used for space heating and for the utilization of waste heat. In technological processes, in particular for drying grain, heat pumps were not widely used, since their design does not allow to achieve high air performance.

The maximum temperature that can be obtained using a heat pump installation is limited by the parameters of the refrigerant.

The main parameters of the heat pump are the temperature of the evaporator \( T_e \), the temperature of the condenser \( T_c \), the cooling capacity \( Q_c \), and the heating capacity \( Q_{hc} \). In addition, it is necessary to know the temperature and humidity of the ambient air \( (T_0; w_0) \), the drying agent \( (T_1; w_1) \) and the spent drying agent \( (T'_1; w'_1) \), as well as the humidity of the material before \( (w_w) \) and after \( (w'_w) \) drying.

A distinctive characteristic is that the heat recovery coefficient of modern HPI reaches a value of 7.5, which suggests that at a cost of 1 MJ of mechanical or electrical energy, the heat production is about 7.5 MJ. Thus, we can conclude that the efficiency of HPI is 750%, which is a mistake.
To assess the required heat recovery coefficient for HPI when creating a drying agent, it was necessary to evaluate, first of all, the cost of energy in monetary terms for drying 1 kg of grain.

When using a gaseous fuel burner, the production of 730 MJ of thermal energy requires the use of 0.2 m$^3$ of natural gas. With the cost of natural gas in the Russian Federation according to 2020, 5.2 rubles / m$^3$ (for a private consumer), the energy cost in monetary terms for creating a drying agent for drying 1 kg of grain is about 1 ruble.

When using tubular electric heaters for electric energy to produce 92 MJ of thermal energy, 25.5 kWh of electricity must be consumed. When the cost of electricity is 1.4 rubles / kWh (one-rate tariff for a legal entity), the cost of energy in monetary terms for the creation of a drying agent for drying 1 kg of grain is about 36 rubles.

When using HPU for electric energy for the production of 87.5 MJ of thermal energy, it is necessary to use 87.5 / (3.6 K) kWh of electricity. When using HPI with an air-to-air circuit and an average heat recovery coefficient of $K = 4$, the energy cost in money terms for creating a drying agent for drying 1 kg of grain is about 9 rubles.

The data clearly show that the use of an air-to-air HPI requires lower costs for drying grain than a tubular electric heater (TEH), however, more than burners.

For experimental confirmation of the possibility of using HPI to create a drying agent, it is necessary to determine the maximum temperature of the obtained drying agent, as well as the heat recovery coefficient. The experimental model of HPI is assembled using elements of refrigeration equipment. The heat exchanger creating a drying agent is shown in Figure 2.

![Figure 2. Photo of a heat exchanger creating a drying agent HPI.](image)

The experimental data showed that the maximum temperature of the drying agent obtained by the experimental model of HPI is +63 °C, while the heat recovery coefficient is about $K = 3$.

Thus, the cost of drying 1 kg of grain in cash is about 12.5 rubles for the cost of electricity to create a drying agent. The electric power the compressor of HPI is 350 W.

Laboratory studies of HPI as a source of thermal energy to create a drying agent and a cooling agent show the prospect of their use.

To reduce the energy consumption for the creation of an agent when using HPI, modernization of the structure is necessary.

To confirm the theoretical assumptions of the possibility of using HPI in the drying process of grain, it is necessary to develop, assemble and test a prototype seed dryer.
The grain dryers used in our country and abroad are very diverse in terms of drying method, design of the drying chamber, state of the grain layer, operating mode, and many other technological and structural features. Therefore, it is difficult to give a single classification, covering the entire variety of dryers for the entire set of distinctive features. It is advisable to classify dryers according to some of the most important features, such as the method of supplying heat, the state of the grain layer, the design of the drying chamber, the operating mode, the drying process diagram, and the design.

Given the possibility of using a heat pump as an energy source for drying seeds, it is proposed to use a conveyor dryer of low productivity.

Like all common grain dryers, the prototype consists of the following elements:
- Device for creating a drying agent;
- Device for creating a cooling agent;
- Drying chamber;
- Boot device;
- Unloading device;
- Ventilation system;
- Instrumentation and automation.

As devices for creating a drying and cooling agent, a condenser and evaporator HPI are used, respectively. Thus, the HPI will have an air-to-air circuit, which will simplify installation, commissioning, maintenance and cost.

As a drying chamber, a conveyor belt is used, made of a flexible food net with fine perforation. The camera is a cube whose faces are made of a corner and are stiffeners, and the planes are made of heat-insulating material. In the inner part of the drying chamber there is a belt conveyor with a tensioning device and leveling belts.

The loading device is a slide gate, with which the grain is fed to the conveyor belt evenly, and the amount of material supplied is also regulated.

The unloading device is a funnel in which the grain is collected, falling from the belt under its own weight at the bend of the conveyor.

The ventilation system is an axial fan designed to force the movement of air masses inside the drying chamber through a layer of processed grain.

Instrumentation and automation are: temperature sensors of the surfaces of the condenser and evaporator HPI; thermohygrometers of the state of drying / cooling agent and ambient air; grain moisture meter; voltage regulators for adjusting the performance of fans; electromagnetic starting and thermal relays of a single-phase asynchronous motor HPI, as well as indicators of the installation and control buttons.

Also, a prototype grain dryer has the ability to create a drying agent with the use of TEH for a comparative assessment of the efficiency of the installation.

A sketch of a prototype grain dryer is shown in Figure 3.

As can be seen from the sketch, HPI is designed to create drying and cooling agents. By using air ducts, a drying and / or cooling agent is supplied to control the necessary parameters inside the drying chamber. In addition to the HPI, a drying agent can be created with the help of a heater installed directly in an additional duct. Sensor locations are also indicated in the sketch.

Grain is fed into the hopper, from which it spills onto the conveyor by gravity, is distributed in a thin layer and moves along the surface of the first upper conveyor, where drying occurs, then the lower one, where cooling takes place. Drying and cooling agent is pumped by fans from heat exchangers and moves perpendicular to the direction of movement of the material. Using the sleeves, the spent agent is taken from the drying and cooling chamber, after which it is cleaned, drained and then fed back to the dryer. The drying mode is regulated by changing the temperature of the coolant and the speed of the conveyor of the drying chamber.

The design of this dryer eliminates mechanical trauma to the grain; to achieve the absence of grain losses with spent drying agent; Meets modern requirements for protecting the environment and grain material from harmful emissions due to the absence of combustion products; has small dimensions.
The drying mode can be adjusted by changing the temperature of the coolant and the speed of the conveyor of the drying chamber. The feed can be controlled using the hopper flap.

![Figure 3](image). The sketch of a prototype seed dryer. Legend:
1 - Drying chamber;
2 - Conveyor perforated conveyor;
3 - Loading device;
4 - Unloading device;
5 - ventilation system;
6 - Electric conveyor;
7 - Duct system;
8 - Heating elements (TEH);
9 - Evaporator HPI;
10 - Capacitor HPI;
· - Thermometer;
* - Thermohygrometer

The drying of grain is based on the phenomena of heat transfer from the drying agent to the grain, evaporation of moisture from the grain surface to the environment, moisture transfer from the inner layers of the grain with greater moisture content to the grain surface with lower moisture content, moisture transfer from layers with a higher temperature to layers with a lower temperature.

In the practice of agricultural production, the convective method of drying the grain with a drying agent is mainly used. In this case, heating of the grain occurs, absorption and removal of moisture from the grain mass [2].

After drying the grain with hot air, it must be cooled in order to maintain germination and its other qualities, to prevent self-heating of the grain and to reduce the activity of microorganisms contained in the grain mass.

Existing active ventilation systems have low specific air supply, significant metal consumption and insufficient reliability; in most cases, drying and active ventilation processes are considered separately and do not complement each other.

To solve this problem, the cooling of grain by air, dried and cooled using a heat pump, was used. To complete a prototype of a grain dryer, an electrical circuit was developed, shown in Figure 4.

The operation of the circuit is as follows.
When the QF circuit breaker is turned on, the equipment power circuit is prepared. When the switch S1 is turned on, the power circuit of the working winding of the single-phase asynchronous motor of the compressor M1 is formed through the closed contacts of the thermal relay KT1 and the coil of the electromagnetic starting relay KM. With an increase in the current through the KM coil as a result of the fact that the motor rotor does not yet rotate, the contacts of the KM electromagnetic starting relay are closed and the power supply circuit of the starting winding of the single-phase asynchronous motor M1 is formed and it is started. After starting, the current flowing through the KM coil decreases and the contacts of the starting relay open, voltage is supplied exclusively to the working winding of the single-phase asynchronous compressor drive motor - the engine runs in nominal mode. When the switch S1 is turned off or when the contacts of the thermal relay KT1 open, as a result of overheating of the engine, the M1 motor power supply circuit opens - the compressor stops.

When the switch S2 is turned on, the power circuit of the conveyor motor M2 is formed by means of an AT1 voltage autotransformer. When switching the number of turns of the winding of the AT1 autotransformer, the output voltage changes and, as a result, the engine speed M2. When the switch S2 is turned off, the power supply circuit of the M2 engine is broken - the engine stops.

When the S3 switch is turned on, the power circuit of the conveyor electric motor M3 is formed by means of an AT2 voltage autotransformer. When switching the number of turns of the AT2
autotransformer winding, the output voltage changes and, as a result, the engine speed is M3. When the switch S3 is turned off, the power supply circuit of the M3 engine is broken - the engine stops.

When the switch S4 is turned on, the power circuit TEH F is formed through the closed contacts of the thermal relay KT2, the TEH heats the air. When the heater overheats or the S4 switch trips, the power supply to heater F is interrupted.

Using the developed control scheme, a series of control experiments was carried out, which fully confirmed all the assumptions made above. However, controlling the operation of a heat pump is not a fully understood process.

The main parameters of the HPI, which can be varied:
- compressor operating time;
- rotation speed of the rotor of the motor of the compressor electric drive (productivity, pressure difference).

Parameters that must be adjusted by variations:
- refrigerant pressure in the evaporator / condenser;
- temperature of the condenser / evaporator;
- heat and cooling capacity.

The parameters that need to be adjusted depend on the following indicators:
- initial grain temperature;
- initial grain moisture;
- ambient temperature;
- humidity of air;
- the required final moisture content of the grain;
- grain storage temperature;
- cultivated culture;
- weediness of grain;
- grain dryer performance.

The developed HPI control scheme was a manual control scheme. However, to conduct full-fledged research and bring the laboratory sample to semi-industrial, it was necessary to develop an automatic or automated control scheme.

To automatically control the operation of the HPI, it is necessary to develop a controller controlled by a computer program depending on environmental conditions and parameters of the grain material before and after drying. In addition to the development of an automatic control system for the operation of HPI, it is necessary to improve the design of the drying and cooling chamber.

Existing HPIs allow you to adjust only runtime and coolant flow. By modernization, the HPI device is divided into two circuits (heating circuit and cooling circuit) in which phase transitions occur under the influence of the pressure difference at constant boiling temperatures, depending on the circuit pressure. The pressure difference is created due to the operation of the compressor for injection of refrigerant (RA) and due to the operation of the throttling device to reduce pressure. The pressure difference directly depends on the volume of RA in the HPI, which imposes its own restrictions on the boiling point of RA and pressure in the circuits. Theoretically, the temperature control of the circuits can be carried out by changing the compressor performance, changing the diameter of the throttle bore and, as a result, the volume of RA, which will lead to an increase in the number of working mechanisms and a decrease in the reliability of HPI. Therefore, to expand the number of adjustable parameters, it is necessary to introduce additional elements into the design of HPI - heat accumulators [4].

Schematic diagram of HPI with heat accumulators is presented in Figure 5.

Figure 5. Schematic diagram of HPI with heat accumulators.

A distinctive feature of this design is that the use of heat accumulators allows you to add to the "range" of adjustable temperature parameters of the coolant.

Heat exchangers 6 are designed to create a drying agent and a cooling agent. Moreover, the number of heat exchangers on the side of each circuit (heating, cooling) is equal to two, which ensures the need for supplying or removing additional amounts of thermal energy during operation. The recirculation pump 5 is designed to supply a liquid coolant to the heat exchanger. The heat accumulators 4 are containers with heat exchangers of the heat pump circuits and inserts from a
material having a high heat capacity. Compressor 1, throttle 2, expander 3 and two heat exchangers, which are located in different heat accumulators, represent one circuit of the heat pump.

The heat pump circuit is filled with RA in the gaseous state. The circuit is conditionally divided into two parts: on the left side of the compressor and throttle (low pressure - cooling); on the right side from the compressor to the throttle (high pressure - heating). During operation of compressor 1, the refrigerant moves in the direction indicated by the black arrow, while on the right side of the circuit between the compressor and the throttle valve RA is under high pressure. The boiling point at high pressure corresponds to a higher value, as a result of which RA begins to change from a gaseous state to a liquid state (to condense), thereby transferring thermal energy to the right heat accumulator. The temperature of the coolant in the right heat accumulator increases. From the right side of the circuit, liquid refrigerant is supplied to the left side of the circuit, passing through the throttle, while the pressure decreases and at the same time the boiling point. RA begins to transition from a liquid state to a gaseous state (boiling), taking thermal energy from the left heat accumulator. In this case, the coolant temperature in the left heat accumulator decreases. Thus, the operation of the heat pump is based on the transfer of thermal energy from a less heated region to a warmer one due to the compressor moving to move RA.

During the operation of the HPI circuit I in the heat accumulator circuit II, the coolant is cooled to negative temperatures caused by the pressure XA in the cooling circuit to create a cooling agent in the heat exchangers (the temperature of the cooling agent is regulated by the capacity of the recirculation pumps 5 and the coolant temperature), and in the circuit III the coolant is heated to a high temperature to create a drying agent.
Figure 6. The algorithm of the controller for controlling the heat pump installation. The designations of the format $<TS1>$ indicate the assignment of a control value for the readings of the sensor TS1 controller circuit.

When the unit is turned on, the temperatures are the same in all parts of the unit. Starting is done by starting the compressor motor of the HPI circuit. The compressor begins to work on moving the RA and creating a pressure difference in the HPI heat exchangers.

During compressor operation, it is necessary to control the pressure values on both sides of the compressor. If the pressure exceeds a critical pressure, it is necessary to protect by disconnecting the compressor drive. When the pressure drops below the minimum, which is possible during depressurization of the system, the compressor stops. If during operation part of the RA in the cooling circuit does not have time to go into a gaseous state, then a hydraulic shock in the compressor is possible. To prevent water hammer, an expander is provided that eliminates the supply of liquid RA to the compressor. If during operation the expander does not provide protection against water hammer, then, due to an increase in the load on the compressor drive motor, it is necessary to reduce the compressor speed in order to reduce productivity. The compressor speed is reduced by introducing additional resistances into the stator windings.

When the temperature of the coolant in the heat accumulator reaches the optimum value, recirculation pumps are switched on. If the optimum temperature in one of the circuits is reached and the optimum temperature in the other circuit is not reached, the second recirculation pump is switched on in the circuit with optimal parameters. These actions are designed to comply with the heat balance of HPI and prevent emergency operation of the compressor.
This description of the operation of the installation corresponds to the algorithm shown in Figure 6. To ensure the automatic operation of the installation, according to this algorithm, a prototype electrical circuit is developed, shown in Figure 7.

The developed control algorithm provides for the independent operation of the HPI compressor and coolant supply pumps, which reduces the risk of emergency situations during operation of the grain dryer.

The controller circuit is activated by turning on the QF3 circuit breaker, which, in turn, serves to protect the control circuit from emergency conditions (short circuit, continuous maximum permissible current). At the moment of activation of the controller, the controls for heating and cooling circuits, as well as the controls for additional cooling and additional heating, start working.

To enter the HPI compressor, press the "START" button S1. If the RA pressures in the HPI circuits deviate from the norm, switching on is not possible. Several hardware solutions are provided to protect the compressor motor:

- protection by the QF1 circuit breaker against short circuit currents in case of jamming of the motor or damage to cable and wire products;
- protection by a circuit breaker QF1 from long overload currents in the event of mechanical failure of the compressor or engine failure due to various reasons;
- protective shutdown of the compressor engine due to the operation of the thermal relay TR1 in case of overheating of the motor windings, breakage of one or more phases, phase imbalance, water hammer and other reasons;
- the introduction of additional resistances R to the compressor drive motor circuit by activating the thermal relay TR2 to reduce compressor performance in order to prevent possible emergency situations during HPI operation;
- compressor operation is blocked if the maximum pressure of the circuit is exceeded due to the operation of the PS2 pressure sensor in the event of a water hammer or a failure of one or more heat accumulator circuits.

During the operation of the HPI compressor, the temperatures of the heat accumulators of the heat accumulators change according to various laws, therefore the operation of the equipment of the heat accumulator circuits is independent.

The pumps and fans of the heating circuit are switched on automatically when the minimum set value set by the TS1 sensor is reached. The coolant flow in the heat exchanger circuit is carried out automatically according to the temperature parameters of the coolant returning from the heat exchanger to the heat accumulator.
Figure 7. The electric circuit of the controller on electromagnetic relays. Prototype. Where: KM0-KM6 - electromagnetic relay; QF1; QF3 - automatic protection devices; S1 - START button; S2 - STOP button; TR1 - protective thermal relay of the compressor engine; TR2 - adjustable thermal relay of the compressor engine; R - additional resistance of the compressor motor circuit; PS1-PS2 - HPI refrigerant pressure sensors; TS1; TS3 - adjustable temperature sensors for coolant circuits; TS2; TS4 - temperature sensors of the coolant protection circuits; RR1-RR2 - customizable thermal resistance regulators; CA1-CA2 - customizable agent flow controllers.
If the coolant temperature in the heat accumulator reaches the boiling point RA in the HPI condensation circuit, an additional heating circuit is automatically switched on, which prevents the HPI from operating in emergency mode due to the additional removal of thermal energy.

The operation of the controller from the side of the cooling circuit is carried out in a similar way according to the operation algorithm.

3. Conclusion
Based on the results of the work, the following conclusions and conclusions were obtained.

The main factors determining the consumption of thermal energy in existing drying schemes are:
- initial grain moisture (before drying);
- final grain moisture (after drying);
- ambient temperature;
- humidity of air;
- grain heating temperature;
- consumption of drying agent;
- efficiency of furnace devices and heat exchangers.

Having analyzed the equations of the heat balance of grain drying, we can draw the following conclusions:
- the proportion of the cost of thermal energy carried away by the spent drying agent is approximately 45-50%;
- the cost of thermal energy during drying can be reduced by removing moisture during cooling.

It is possible to reduce the need for thermal energy in the process of drying grain due to:
- reduce the initial humidity of atmospheric air;
- reducing the consumption of spent drying agent;
- reducing the pressure of the drying agent;
- increase the temperature of the spent drying agent;
- increase the humidity of the spent drying agent;
- increase the efficiency of the thermal system of the dryer;
- the use of thermal energy recovery devices or alternative sources of thermal energy.

As a device for creating a drying agent and a cooling agent at a capacity of 1 ton / hour, a heat pump unit with the following parameters can serve:
- minimum electric power of the compressor - 45.5 kW;
- minimum compressor refrigerant transfer capacity is 2.1 kg / s;
- brand of refrigerant - R142b;
- the minimum pressure difference created by the compressor is 1.44 MPa;
- boiling point at low pressure (evaporator) – 0 °C;
- boiling point at high pressure (condenser) – 90 °C;
- the minimum heat transfer area of the evaporator is 8 m²;
- minimum condenser heat transfer area - 22 m².

The calculated data show that the minimum thermal characteristics for drying 1 ton of grain are:
- heating capacity - 651 kW;
- cooling capacity - 38 kW.

At the same time, the consumption of drying and cooling agents should be at least:
- consumption of drying agent for heating grain - 0.91 kg / s;
- consumption of drying agent for evaporation of moisture - 2.4 kg / s;
- the consumption of the cooling agent to reduce the temperature of the grain is 2.3 kg / s.

The calculations are carried out for the following conditions:
- ambient temperature during the drying period – 15 °C;
- humidity of air - 75%;
- grain dryer productivity - 1 ton / hour;
- initial grain moisture - 24%;
- final grain moisture - 14%;
- cereal - wheat;
Using HPI as a source of thermal energy to create a drying agent during grain drying is advisable only if it is not possible to use gas burner devices.

Prerequisites for using HPI include:
- the use of gas equipment in the household exclusively for the needs of drying;
- the need to use low-capacity grain dryers;
- the use of designs of mobile grain dryers;
- the need to create a cooling agent with a low temperature.

Experimental studies have confirmed the possibility of using HPI as a source of thermal energy to create a drying agent. The following results were obtained on the characteristics of the experimental HPI model for creating a drying / cooling agent:
- maximum temperature of drying agent + 63 °C;
- maximum condenser temperature + 90 °C;
- the minimum temperature of the cooling agent + 5 °C;
- the minimum temperature of the evaporator is -18 °C;
- HPI circuit - “air-to-air”;
- heat return coefficient 3;
- electric power of the compressor 350 W.

To further confirm the feasibility of using HPI, the drying chamber was assembled and comparative operations were carried out to dry grain lots using HPI and using TEH with an assessment of their energy intensity.

Using HPI as a source of thermal energy to create a drying agent during grain drying is advisable only if it is not possible to use gas burner devices.

Prerequisites for using HPI include:
- the use of gas equipment in the household exclusively for the needs of drying;
- the need to use low-capacity grain dryers;
- the use of designs of mobile grain dryers;
- the need to create a cooling agent with a low temperature.

A prototype laboratory setup, as well as an electrical control circuit, has been developed. A series of experiments was carried out, the results of which indicate the prospect of developing the topic of using HPI as an alternative source of thermal energy in the drying process of grain (to create a drying agent and a cooling agent).

The HPI control controller is designed for automatic operation of a grain dryer based on a heat pump installation.

The scheme allows you to automatically support:
- the set temperature of the drying agent;
- predetermined consumption of the drying agent;
- the set temperature of the cooling agent;
- the specified flow rate of the cooling agent.

The controller operation algorithm provides the following types of protection:
- controller elements from short circuit currents and long overload currents;
- compressor motor from short circuit currents, long overload currents;
- compressor motor from breaking one or more phases, from phase imbalance, from overheating of the working windings;
- compressor against water hammer;
- turning on the compressor in case of refrigerant leak;
- from excessive heating of the heat carrier of the heat accumulator of the heating circuit;
- from excessive cooling of the heat carrier of the heat accumulator of the cooling circuit.
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