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New Technical Approaches to Drying Agricultural Foods

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ABSTRACT

The use of a refrigeration cycle to raise the temperature has a long history — for the first time such an idea was expressed in 1852 by William Thomson. This article is a theoretical paper devoted to evaluating the possibility of increasing the efficiency of a convective dryer using a heat pump refrigeration unit. The authors of the article present the principle of operation and a constructive calculation of a heat pump refrigeration unit with the construction of its cycle on the Ts diagram for the selected refrigerant (R134a). The analysis of the thermodynamic cycle of the compression heat pump refrigeration unit and the calculation performed for freon R134a show that the selected refrigerant fully provides all operating modes of the convective dryer. The main advantage of the proposed heat pump refrigeration unit for drying is the possibility of returning the latent heat of steam obtained from the moisture of the dried product by reverse condensation of water vapor contained in the spent drying agent (air). A wind turbine can be included in the design of the presented convective dryer, which will generate electrical energy using a generator. For each 1 kW (0.9478 Btu/s) of electricity paid, the user will receive 4.25 kW (4.0282 Btu/s) of free thermal energy. This offers an additional solution for the practical needs of agriculture and the food industry.

1. Introduction

The removal of moisture from substances (products) as a result of evaporation and removal of the resulting vapors under the heat treatment is called drying. When drying, a volatile component, water, is removed from substances (products) in the vapor form.

Many types of fruits, vegetables and cereals can be stored only for a very short time after harvesting. Their long-term storage is possible only after drying these fruits, vegetables and cereals. The most common type is convective drying, which occurs by direct contact of the dried material (product) with a drying agent, which is usually heated air. In the convective drying process, when water is removed using a stream of hot air, the processes of heat transfer, mass transfer and amount of movement transfer will occur simultaneously. The convective dryer is based on the processes of heat and mass transfer due to diffusion, convection and evaporation.

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During convective drying, heated humid air performs two functions: 1) it transfers heat to the product; 2) it removes moisture evaporating from the product due to this heat. Thus, heated humid air plays the role of a heat and moisture carrier. As a result of convective drying, the stability of food products improves, since the mobility and activity of water in them are significantly reduced and, as a result, chemical and microbiological changes during storage are minimized. Thus, the shelf life of food products is significantly increased.

The quality of the drying process can be influenced by a number of factors: temperature, speed, relative humidity, moisture content in the product, composition, texture and porosity of the product. Thus, during the convective drying process, it is necessary to constantly monitor the temperature and air velocity in the dryer in order to ensure optimal operating parameters for a particular product (substance).

The results of a numerical study are presented and a model is developed and refined for the Page kinetics of convective drying of yacon plates (a root crop growing in the Andes) were presented. The authors evaluated the effect of air velocity on the temperature regime in the heating area of a convective dryer with a tray, whose the main parameters were controlled by a proportional-integral-differential control system. The air velocity in the dryer varied in the range of 0.81 - 2.06 m/s (2.66 - 6.76 ft/s) at a constant temperature of 70 °C = 158 °F. The optimal value of the air velocity in the dryer (1.46 m/s = 4.79 ft/s) was determined, at which the temperature signal was the most stable and closest to the reference temperature for convective drying of the yacon plates.

A study of the effect of air velocity and temperature in a convective dryer, and the power of infrared radiation and the distance between samples in an infrared dryer on the kinetics of drying and the quality of slices of a drug with a high content of antioxidants and calcium - ganoderma lucidum was published [2]. The air velocity in the dryer varied in the range of 0.5–1.5 m/s (1.64 - 4.92 ft/s) and the temperature varied in the range of 40-60 °C (104-140 °F). The infrared radiation power varied in the range of 500-1500 Watts (0.474-1.422 Btu/s), and the distance between the samples was 4-16 cm (0.13-0.53 ft). Kinetic research has shown that an infrared dryer has better characteristics than a convective dryer in terms of the time to reach an equilibrium moisture content during drying, energy consumption, the amount of calcium and the antioxidant content of ganoderma lucidum.

The processes of hot air drying are investigated [3] for three types of freshwater fish (with and without scales) using a convective air dryer of authors' own production. The total drying time was 14-20 hours. The air velocity in the dryer corresponded to 0.5 m/s (1.64 ft/s), while the temperature varied in the range of 60 – 140 °C (140 -284 °F). To study the kinetics of drying freshwater fish with and without scales using simplified solutions of Fick's law, the heat balance equation and the Lewis ratio, the calculated coefficients of mass transfer ((2.8–4.5) × 10^{-6} m/s = (9.19–14.76) × 10^{-6} ft/s), convective heat transfer (7-14 W/($m^2 \cdot K$) = ((3.43–6.85) × 10^{-4} (Btu/s)/($ft^2 \cdot °F$)) and effective diffusion ((0.2–1) × 10^{-9} m^2/s = (2.153–10.764) × 10^{-9} ft^2/s) were determined. To reveal a more complete picture of the convective drying process, the average and local amounts of total energy consumed, the specific moisture extraction coefficient and the specific energy consumption were also determined. An analysis of the empirical data obtained showed a higher degree of effective diffusion when drying fish without scales compared to fish with scales present. A good degree of consistency of the calculated data with the results gained experimentally has been obtained.

Some authors of have developed a design of a hybrid multipurpose bithermal convective dryer for drying various food and pharmaceutical products [4] . The design of the dryer implements thermal insulation measures to reduce heat losses in order to enhance the stability of the thermal balance in the drying chamber, which is able to ensure uniform drying at an adjustable time. The dryer design suggests both joint and separate use of gas heating and drying using an electric heating element

(filament) due to effective dual temperature control in the drying chamber. The effect of the drying temperature in a convective dryer on ripe and unripe banana samples from Nigeria was experimentally investigated [5]. The samples were washed, peeled, and cut into pieces of 20 grams (0.044 lb) each. Next, they were loaded into a convective dryer chamber and removed from the chamber every hour to measure moisture loss. The drying temperature ranged from 333 K (139.73 °F) to 353 K (175.73 °F). The results of the laboratory analysis showed that the number of viable microbes decreases with increasing drying temperature. Ripe banana samples were found to have a higher percentage of crude fiber, fat, and protein than unripe samples, while unripe samples had a higher percentage of carbohydrates and ash than ripe samples at the same drying temperatures. It was found that the number of microbes (bacteria and fungi) is higher in unripe banana samples than in ripe samples, and thus immature banana samples are better preserved than ripe ones.

It is important to keep in mind that drying in an infrared dryer can cause irreversible degradation of various nutrients contained in food products. In addition, drying in an infrared dryer is a much more expensive method than drying products with heated air using convection. That is why this article studies the issues of improving the efficiency of a convective dryer. The energy efficiency of a convective dryer can be improved by including a heat pump refrigeration unit in its design, which will allow the use of secondary energy resources and rational energy consumption directly during the drying of agricultural products. This design will reduce the consumption of organic fuels, reduce environmental pollution and prepare sufficient thermal energy for the needs of consumers.

Heat pump refrigeration units have emerged as promising solutions for the sustainable production and recovery of thermal energy with a number of implementation options (hot water supply systems, convective drying, etc.). A heat pump refrigeration unit is an energy equipment that converts low-potential renewable energy from natural heat sources or low-temperature secondary energy resources into energy of higher potential suitable for practical use. The reverse refrigeration cycle of a water-to-water heat pump was experimentally studied for various operating parameters of a power plant [6]. The study was performed under the operating conditions of the cooling mode. Using the COOL PACK software package, the cycles of the heat pump were plotted in logp-h- and p-s-diagrams, and thermodynamic parameters of the R407C refrigerant state were obtained at characteristic points of the cycle. Based on the results obtained, the specific heat of vaporization, the specific work of compression, and the specific heat of condensation were determined, and the value of the refrigeration coefficient of the power plant was obtained.

The cycle of a coupled thermodynamic system - a heat pump and a refrigeration unit - is considered based on the method of exergetic analysis [7]. For the production of thermal energy for the heat pump cycle, wastewater heat from an industrial process with a temperature above ambient temperature and a working medium, the refrigerant freon R134a, are used. Carbon dioxide CO_2 is used as a working medium for the production of cold in a refrigeration unit. Using exergetic analysis, the possibility of optimizing the reverse cycle of a coupled thermodynamic system is considered by introducing a supercooling process into both the heat pump cycle and the refrigeration unit cycle in order to improve the functional structure and design of the equipment.

Heat pump technology was implemented for heat recovery of secondary energy resources in a catalytic method for producing biodiesel [8]. The heat pump system is presented in the form of two recirculation circuits for low-potential and high-potential heat carriers, which were prepared at the low-pressure and high-pressure stages of the heat pump. An exergetic analysis was performed, and functional dependences of the exergy flows coming from the considered types of technological equipment were obtained. The resulting hybrid fuel met the requirements of the government standard GOST 23513-79. The proposed heat pump technology has reduced specific energy consumption by 13-14 %.

A virtual model was developed for a refrigeration cycle and a heat pump cycle with variable flow rate in order to ensure the operation of heating, ventilation and air conditioning systems in buildings, which has various combinations of internal units for the possibility of cooling and heating in extreme weather conditions [9]. The developed virtual model was tested and its operation was verified using local data obtained during field measurements.

Various compression cycles of ejector heat pumps and refrigeration units are considered and evaluated [10]. These heat pumps and refrigeration units can eventually replace conventional steam compression heat pumps. One- and two-ejector compression cycles are presented.

Drying plants are currently the most rational area for the introduction of heat pump refrigerating units for the preparation of a drying agent (heated humid air). Such constructions are successfully used for drying medicinal herbs and food. The spent drying agent, that is, an air-steam mixture removed from the drying chamber, is used as a source of low-potential heat of the drying chamber. The purpose of this study is to develop recommendations for determining the design parameters of a convective dryer with a heat pump refrigeration unit, which will improve the quality of agricultural products and ensure their long-term storage.

When drying, a volatile component, water, is removed from substances (products) in the vapor form. The most common type is convective drying, which occurs by direct contact of the dried material (product) with a drying agent, which is usually heated humid air. During convective drying, heated humid air performs two functions: 1) it transfers heat to the product; 2) it removes moisture evaporating from the product due to this heat. Thus, heated humid air plays the role of a heat and moisture carrier. The energy efficiency of a convective dryer can be improved by including a heat pump refrigeration unit in its design, which will allow the use of secondary energy resources and rational use of energy directly when drying agricultural products. This design will reduce the consumption of organic fuel, reduce environmental pollution and prepare thermal energy in sufficient quantities for the needs of consumers. After harvesting, many types of fruits, vegetables and cereals can be stored for a very short time. Their long-term storage is possible only after drying these fruits, vegetables and cereals. A heat pump refrigeration unit is an energy equipment that converts low-potential renewable energy from natural heat sources or low-temperature secondary energy resources into the energy of higher potential which is suitable for practical use. Drying plants are currently the most rational area for the introduction of heat pump refrigeration units for the preparation of a drying agent (heated humid air). Such constructions are successfully used for drying medicinal herbs and food products. As a source of low-potential heat of the drying chamber, a spent drying agent is used, that is, an air-steam mixture removed from the drying chamber.

2. Methodology

The heat of the spent drying agent after increasing its potential in a heat pump refrigeration unit is used both to heat the supply air delivered to the drying chamber and to maintain the required temperature and humidity regime. The first implementation of a heat pump refrigeration unit in practice was carried out by Peter Rittinger in 1855, however, the widespread use of such machines began only from the 1930 – 1940s. According to [11], in 1943, the Sulzer company developed a heat pump refrigeration unit, which was used for dewatering and desiccation of underground cavities and voids in a number of regions of Germany. In 1950, a grain dryer was developed in the USA, in which moisture was removed from grain crops due to evaporation and removal of the resulting vapors under heat treatment. A significant part of the work using heat pump refrigeration units is not related to conventional convective drying, but to freeze drying [12], in which conventional refrigeration equipment is used to freeze the product. To assess the energy possibilities of using heat pump

refrigeration units during desiccation, the dependences were found for the maximum heating coefficient of the reverse Carnot cycle on the temperatures of the drying agent at the inlet and outlet of the drying chamber and on the temperature difference in the dryer [13]. The authors of the paper [14] conducted a numerical experiment and formulated recommendations on the choice of heat pump refrigeration units in relation to various production processes. It has been established that due to the recovery and modernization of the heat removed, heat pump refrigeration units can save 15...78 % of the hot water consumed, depending on the specific process. Recommendations are given for choosing a specific type of heat pump refrigeration unit from several suitable combinations [15]. Based on the developed simulation model, an analysis and comparison were carried out for the energy and economic characteristics of four types of heat pump refrigeration units [16]. The main types of refrigerants in heat pump refrigeration units are: halogenated limit hydrocarbons (refrigerants), methane, pentane, ammonia, carbon dioxide and absorption working vapors. Air, superheated water vapor and fuel combustion products are usually used as drying agents in drying chambers. The features of most drying processes are relatively high air temperatures at the inlet and outlet of the drying chamber, as well as relatively high performance on evaporated moisture. Therefore, the use of dryers with heat pump refrigeration units is associated with a number of difficulties, which are primarily related to the direct choice of the calculated reverse thermodynamic cycle, a specific working fluid (refrigerant), compressor, heat exchange and dehumidification equipment. Thus, it can be stated that at present there is a need to obtain new information that will allow us to study the issue of developing and designing dryers with heat pump refrigeration units. The purpose of the study is to develop specific recommendations and select design solutions for dryers with heat pump refrigeration units that will effectively convert the energy of secondary energy resources into the energy of higher potential to improve the quality of agricultural products and to ensure the possibility of its long–term storage. The main characteristic of the energy consumption for drying is the heat consumption for evaporation of 1 kg (2.204 lb) of water vapor from an agricultural product. It is known that the heat consumption for evaporation is 2500 kJ/kg (1074.806 Btu/lb) according to theoretical calculations [17]. The drying plant itself creates secondary energy resources as the heat of the exhaust air and the steam generated during drying. The latent heat of vaporization and the heat of the heated air itself are usually lost when they are released from the drying plant into the atmosphere. In traditional dryers, due to the losses, the value of heat consumption for evaporation of 1 kg (2.204 lb) of water vapor from an agricultural product exceeds the value of 6000 kJ/kg (2579.536 Btu/lb) [17]. Table 1 shows the energy costs of drying various products.

Table 1
The energy costs of drying agricultural products [17]

Agricultural product	Moisture content, %		The required amount of moisture, kg/t, lb/t	Air temperature for drying, °C, °F	Specific cost per 1 kg of evaporated moisture, kJ/kg, Btu/lb
	initial	final			
Grain crops	18	14	46.7 (102.93)	40...100 (104...212)	4000...6200 (1719.69 .. 2665.52)
	22	14	102.6 (226.13)	40...100 (104...212)	3700...6000 (1590.714 .. 2579.536)
Rape plant	18	10	97.6 (215.11)	40...60 (104...140)	3700...6200 (1590.714 .. 2665.52)
	22	8	179.5 (395.62)	40...80 (104...176)	3700...6000 (1590.714 .. 2579.536)
Corn	35	14	323.1 (712.11)	50...110 (122...230)	4600...6200 (1977.644 .. 2665.52)
	40	14	433.3 (954.99)	50...110 (122...230)	3700...6000 (1590.714 .. 2579.536)
Ventilated dried hay	35	16	292.3 (644.23)	20...40 (40...104)	3700...6200 (1590.714 .. 2665.52)
	45	16	327.3 (721.37)	20...50 (68...122)	4000...6700 (1719.69 .. 2880.482)
	55	16	366.7 (821.41)	20...80 (68...176)	3700...6000 (1590.714 .. 2579.536)

3. Results

When operating a conventional convective dryer **(Fig. 1)**, the drying agent (air), which provides drying of fruits, vegetables and cereals, with the inlet temperature of t_1 is heated in the heater *2* to the required temperature and enters the drying chamber *3*, where it gets discharged into the atmosphere through the outlet part *4* of the unit.

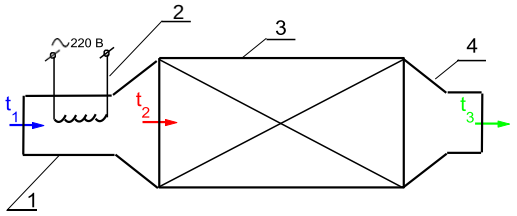


Fig. 1. The conventional convective drying mode

To describe the processes occurring in ventilation and air conditioning systems, as well as in convective dryers, the *hd*-diagram of humid air is used **(Fig. 2)**. The *hd*-diagram was proposed by Professor L.K. Ramzin in 1918. A diagram is plotted for one constant value of the barometric pressure of humid air, which is equal to 745 mm Hg, which is the annual average for the Central European part.

This diagram graphically links all the parameters that determine the heat and humidity state of the air: enthalpy, moisture content, temperature, relative humidity, and partial pressure of water vapor. It is plotted in an oblique coordinate system, which makes it possible to expand the area of graphical design of processes for unsaturated humid air, and makes it convenient for displaying thermodynamic processes implemented in convective dryers.

The diagram field is divided by lines of constant values of enthalpy (*h* = const*)* and moisture content (*d* = const*)*. It also has lines of constant temperature values of *t* =const, which are not parallel to each other. Meanwhile the higher the temperature of the humid air is, the more its isotherms deviate upward. A characteristic feature of using the *hd*-diagram is that if at least two parameters of the air are known, then it becomes possible to obtain all other parameters that determine the heat and humidity state of the drying agent (air) for each point of the thermodynamic process using minimal additional graphical work on it.

Let us depict the thermodynamic processes occurring in a conventional convective dryer on the *hd*-diagram of humid air **(Fig. 2)**. The process of heating the air in the heater is represented by the *AB* segment, which is carried out from point *A* corresponding to the initial state of the air (t_1, φ_1) vertically upward along the line of constant moisture content ($d_1 = d_2 = const$) to the intersection with the isotherm $t_2$corresponding to the air heating temperature.

The *BC* segment (drying process) is drawn downwards from point *B* along the line of constant enthalpy ($h_2 = h_3 = const$) to the intersection with the isotherm t_3 corresponding to the air temperature at the outlet of the drying chamber. In the normal convective drying regime, the entire enthalpy difference between the air states at points *A* and *C* is losses. The specific heat consumption for removing 1 kg of moisture when considering the operation of a conventional dryer significantly exceeds the latent heat of vaporization.

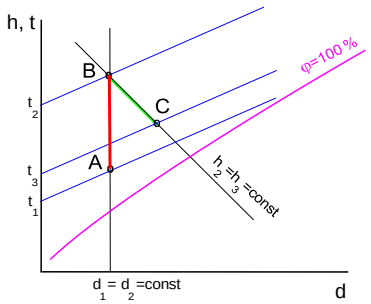


Fig. 2. The *hd*-diagram of humid air

To reduce energy consumption and increase the efficiency when drying fruits, vegetables and cereals, the authors propose to introduce a heat pump refrigeration unit into the design of the convective dryer.

The purpose of the study is to develop specific recommendations and operating schemes for a convective dryer with a heat pump refrigeration unit for drying fruits, vegetables and cereals.
The diagram of the proposed convective drying unit, which works in conjunction with a compression heat pump refrigeration unit to use low-potential thermal energy, is shown in **Fig. 3**.

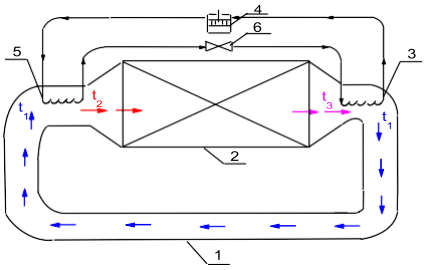


Fig. 3. The diagram of a compression heat pump refrigeration unit

Reverse condensation of vapors from the exhaust air occurs on the walls of the evaporator (**Fig. 3**) and then the drying agent (air) is cooled near the evaporator 3 to almost the dew point

temperature of t_1 . Next, the cooled drying agent is transported through the duct 1 to the condenser 5, where the air is heated to the temperature of t_2, required for the drying process. After the drying agent (air) exits the drying chamber 2, the air temperature becomes t_3. Thus, the drying cycle is completed, which makes it possible to return the heat of evaporation of water vapor condensed from the air, using a heat pump refrigeration unit.

The refrigerating agent (R134a freon) boils in the evaporator 3 at constant temperature T_0 and pressure p_0 (**Fig. 3**), while the low-potential heat q_0 is supplied to it from the drying agent (air), which circulates inside the drying unit. Next, R134a freon in the form of dry saturated steam is compressed by the compressor 4 from pressure p_0 to pressure p_K. During compression, the temperature of the dry saturated steam rises from T_0 to T'_K, and at the outlet of the compressor, the refrigerant becomes superheated steam. It is necessary to constantly spend work on the compressor drive.

Next, compressed R134a freon in the form of superheated steam with an overheat temperature of T'_K enters the condenser 5, where it is first cooled to a temperature of $T_к$ corresponding to the state of dry saturated steam, and then condensed to a liquid state at a constant condensation temperature. During the condensation of refrigerant vapors, the q_K heat is released, which is transferred to the drying agent (air) circulating inside the drying unit. To reduce losses, the liquid R134a freon needs cooling below the condensation temperature, and the supercooling process has to be carried out in the condenser itself.

After the condenser, the liquid R134a freon enters the regulating throttle valve 6, in order to change the flow rate of the refrigerant mechanically. A temperature-regulating expansion valve is used as a regulating throttle valve, which consists of a channel of a certain cross-section, a shut-off needle and a thermostatic system. The main element of the thermostatic system is a membrane, which is affected by the pressure of the refrigerant and the spring on one side, and a thermowell with R134a freon on the other side. If the excess pressure in the thermowell exceeds the operating pressure of the liquid R134a freon in the refrigeration unit by an amount determined by the spring elasticity force, the spring elasticity force of the temperature-regulating expansion valve moves the shut-off needle upward and completely opens the supply of R134a freon to the evaporator 3. If the temperature of the gaseous R134a freon at the outlet of the evaporator decreases, the shut-off needle reduces the channel cross-section of the temperature-regulating expansion valve when moving down, which leads to a decrease in the pressure of the liquid R134a freon, and in this case the throttling process will occur.

The temperature-regulating expansion valve operates cyclically during operation of the heat pump refrigeration unit and is capable of changing the temperature of the gaseous R134a freon at the outlet of the evaporator.

During throttling, no external work is performed, and the enthalpy remains constant. The internal energy of the gas is spent on overcoming the forces of internal friction. The control throttle valve has a simple device and allows you to regulate the supply of the liquid R134a freon to the evaporator 3.

When throttling in the control throttle valve *6*, the temperature of the liquid R134a freon decreases to T_0 according to the Joule–Thomson effect due to the instantaneous evaporation of part of the liquid refrigerant. The heat of evaporation is removed from the rest of the refrigerant mass and the temperature of the freon decreases. Since heat is removed and transferred inside the thermodynamic system without heat exchange with the environment, the enthalpy of the R134a freon remains constant during the process, and the entropy increases.

Then the condensed refrigerant, after reducing the pressure in the control throttle valve 6, re-enters the evaporator 3, and the processes occurring in a convective dryer with a heat pump refrigeration unit for drying fruits, vegetables and cereals are repeated.

The presented convective dryer operates according to the cycle of a heat pumping refrigeration unit with throttling. To analyze the operation of a convective dryer with a heat pump refrigeration unit and describe thermodynamic processes, we design its cycle in a thermal *Ts*-diagram for difluoro-dichloro-methane (**Fig. 4**).

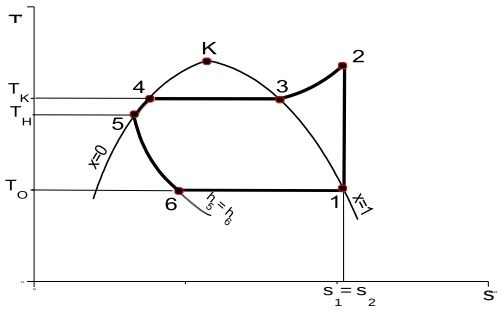


Fig. 4. The thermal *Ts*-diagram for difluoro-dichloro-methane

The operation cycle of a convective dryer with a heat pump refrigeration unit is carried out as follows: 1-2 is the compression of the R134a freon in a compressor; 2-3 is the cooling of the R134a freon in a condenser to a temperature of *T*к corresponding to the state of dry saturated steam; 3-4 is the process of condensation of the freon in a condenser at a constant temperature of $T_к$; 4-5 is the process of cooling the liquid R134a freon below the condensation temperature, occurring in the condenser; 5-6 is the process of throttling the R134a freon in a control throttle valve; 6-1 is the process of boiling the R134a freon in an evaporator.

Using the design of thermal *Ts*-diagram (see **Fig. 4**) it is possible to determine the thermodynamic parameters of the state at the characteristic points of the reverse cycle. The results of processing the *Ts*-diagram are summarized in **Table 2**.

Table 2
Parameters of the state for the working fluid of the heat pump refrigeration unit cycle

Point number	Parameters of the working fluid				
	t_i,, °C, °F	p_i, MPa, psi	?$_i$, m^3/kg, ft^3/lb	h_i, kJ/kg, Btu/lb	s_i, kJ/(kg·K) Btu /(lb. oF)
1	-30 (-22)	0.1 (14.504)	0.149 (2.3868)	559 (240.3267)	4.77 (1.1393)
2	45 (113)	0.75 (108.778)	0.025 (0.4005)	596 (256.2339)	4.77 (1.1393)
3	30 (86)	0.75 (108.778)	0.025 (0.4005)	587 (252.3646)	4.75 (1.1345)
4	30 (86)	0.75 (108.778)	0.0025 (0.04)	449 (193.0353)	4.28 (1.0222)
5	20 (68)	0.58 (84.122)	0.0025 (0.04)	440 (189.166)	4.25 (1.0151)
6	-30 (-22)	0.1 (14.504)	0.05 (0.8009)	440 (189.166)	4.29 (1.0246)

Based on the obtained values of the thermodynamic parameters of the state at the characteristic points of the reverse refrigeration cycle, a design calculation was performed for a convective dryer with a heat pump refrigeration unit based on algebraic equations.

To ensure the circulation of R134a freon with a mass flow rate of M = 0.1 kg/s (0.22 lb/s), a piston compressor with a 2.8 kW (2.654 Btu/s) drive is required. To analyze the possible use of a stall thermal refrigeration unit, the compressor for a throttling cycle was calculated, and the results are summarized in the Table 3.

Table 3
Compressor characteristics of a thermal refrigeration unit

No.	Throttled cycle characteristics	Values
1	G, kg/h, lb/h	360 (793.664)
2	V_D, m^3/h, ft^3/h	53.64 (1894.279)
3	$G^{/}$	7.5
4	λ_i	0.66
5	λ_w	0.8
6	λ	0.528
7	V_h, m^3/h, ft^3/h	101.59 (3587.617)
8	$N^{/}_a$, kW, Btu/s	5.46 (5.175)
9	η	0.725
10	$N^{/}_i$, kW, Btu/s	7.53 (7.137)
11	N_{fr}, kW, Btu/s	2.45 (2.322)
12	N_e, kW, Btu/s	9.98 (9.459)
13	q_v, kW/m^3	798.65
14	K_e	1.19

The design calculation made it possible to determine the main thermodynamic parameters of the drying agent (air) during the operation of the unit at all characteristic points of the closed cycle.
The processes occurring in a convective dryer with a compression heat pump refrigeration unit can be represented on the *hd*-diagram of humid air (**Fig. 5**). To graphically display the processes occurring with the drying agent, we will plot four points of *A*, *B*, *C* and *M* on the *hd*-diagram of humid air according to two known parameters and connect them.

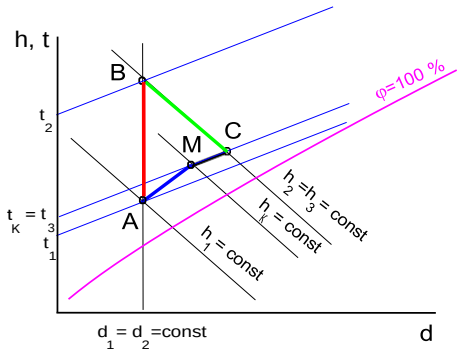


Fig. 5. The *hd*-diagram of humid air

The vertical segment of *AB*, oriented vertically upward along the line of constant moisture content ($d_1 = d_2 = const$) to the intersection with the t_2 isotherm corresponding to the air heating temperature,

represents the heating of the drying agent (air) near the condenser 5. The *BC* line (drying process) is plotted downward from point B along the constant enthalpy line of $h_2 = h_3 = const$ to the intersection with the t_3 isotherm corresponding to the air temperature at the outlet of the drying chamber 2 before it enters the duct 1. The *CM* line represents the reverse condensation of vapors from the exhaust air in the dryer, which occurs on the walls of the evaporator 3. The *MA* segment corresponds to the cooling of the drying agent (air) to almost the dew point temperature of t_1 near the evaporator 3. Thus, the drying cycle of *ABCMA* is closed, which makes it possible to return the heat of evaporation of vapors condensed from the air using a heat pump refrigeration unit.

The exhaust air from the drying unit passes through the evaporator 3 of the heat pump refrigeration unit, where it cools down and gives heat to the refrigerant (R134a freon). The moisture contained in the air is condensed and removed from the convective dryer. To heat the drying agent (air), the heat is used which is equivalent to the heat acquired in the evaporator *3* and the compression of the refrigerant (R134a freon) in the compressor 4.

Having completed additional plotting, we will enter the results obtained using the *hd*-diagram in Table 4.

4. Discussion

A number of theoretical and practical issues related to the advantages and limitations of the proposed approach will be discussed below.

4.1. Assumptions on fixed mass flow rate, idealized thermodynamic behavior - critical evaluation for realism and sensitivity

To evaluate the assumptions used in material drying models, it is important to take into account the actual process conditions and limitations of the models. Let's look at the basic assumptions often used in engineering calculations of drying processes, and discuss their applicability and limitations.

Table 4
Drying agent parameters at operation of a convection dryer with a compression heat pump refrigeration unit

No.	Name of a point of the cycle	Temperature, t_i, °C, °F	Relative humidity, ϕ_i, %	Specific enthalpy, h_i, kJ/kg of dry air, Btu/lb of dry air	Moisture content, d_i, g of moisture / kg of dry air
1	Point A	$t_1 = 15$ (59)	$\phi_1 = 90$	$h_1 = 40$ (17.197)	$d_1 = 10$
2	Point B	$t_2 = 45$ (113)	$\phi_2 = 18$	$h_2 = 70$ (30.095)	$d_2 = 10$
3	Point C	$t_3 = 25$ (77)	$\phi_3 = 88$	$h_3 = 70$ (30.095)	$d_3 = 17$
4	Point M	$t_K = 25$ (77)	$\phi_K = 88$	$h_K = 60$ (25.795)	$d_K = 14$

Main assumptions:

Assumption 1: Fixed mass flow rate. The assumption of a constant mass flow of air or gas used to dry the material is a simplification of the actual process. This assumption is based on the assumption that the air supply rate remains constant throughout the drying process. However, in practice, the mass distribution of the flow may vary due to changes in pressure, temperature, and humidity of the

medium. These factors affect the drying efficiency and should be taken into account when modeling real-world conditions [18].

Since our article presents the initial design calculation of the power plant, it was assumed that the mass flow rate is a constant value. In the future, when working on a mathematical model of a real process, the mass flow rate will be assumed to be variable.

Description of the assumption: it is assumed that the mass consumption of wet material remains constant throughout the drying process. This assumption is convenient for calculating the heat load and the energy required to evaporate moisture.

Error estimation: fixing the mass flow is a rough approximation, since the actual process is characterized by a decrease in the mass of the material as moisture is removed. The error in estimating the thermal balance under this assumption depends on the initial moisture content of the material and the degree of drying. For materials with a high initial moisture content, the error can reach 10% or more.

Assumption 2: Idealized thermodynamic behavior.

Idealization of the behavior of a system assumes that the material and gas behave according to the ideal laws of thermodynamics. For example, it is assumed that heat is transmitted exclusively by convection, neglecting radiation and conduction effects. This approximation greatly simplifies calculations, but it ignores the effects of heterogeneity of the material structure, the presence of temperature gradients inside the sample, and changes in material properties over time [19].

Since our article presents the initial design calculation of a dryer with a heat pump refrigeration unit, it was assumed that the gas has the properties of an ideal gas, which consists of quite elastic molecules, between which there are no forces of mutual attraction and repulsion. At the same time, the volume occupied by the molecules of an ideal gas is vanishingly small compared to the distances between them. Thus, gas molecules are material points.

Description of the assumption

The assumption is that the drying material behaves perfectly according to the laws of thermodynamics, including the constancy of heat capacity, the absence of capillary effects, and a uniform temperature distribution inside the material.

Error estimation

This assumption greatly simplifies calculations, but it ignores important factors affecting the actual processes of heat transfer and mass transfer. For example, changes in heat capacity with temperature and humidity can lead to errors of up to 20%, especially with large temperature changes and significant moisture content.

Other typical assumptions for responding to this remark:

Assumption 3: Uniform distribution of the air flow velocity over the entire volume of the dryer.

Assumption 4: The constancy of heat transfer coefficients on the product surface.

Assumption 5: Linear dependence of water vapor pressure on material temperature.

The last three assumptions also lead to calculation errors, which can vary in the range of 5-15%, depending on the operating conditions of the equipment and the properties of the processed material.

The use of simplified models at the design calculation stage significantly simplifies engineering calculations, but reduces the accuracy of the results. It is important to understand the limits of applicability of each assumption and to take into account possible deviations of the actual values

from the theoretically calculated values. Situations where changes in material characteristics occur rapidly or are non-linear are particularly sensitive. To increase accuracy in the future, the team of authors will use numerical modeling methods that will take into account variable properties of materials and complex environmental conditions.

4.2. discussion of operating conditions and system constraints.

The statement that the mass flow rate of the refrigerant does not affect the performance of the refrigeration unit is indeed overly generalized and requires explanation. Factors affecting the mass consumption of refrigerant:

The 1st factor. Equipment type: Different types of compressors and heat exchangers have different requirements for the mass flow of refrigerant. For example, reciprocating compressors differ from screw or scroll compressors in their sensitivity to changes in the mass of the circulating refrigerant.

The 2nd factor. Environmental conditions: Ambient temperature, relative humidity and atmospheric pressure also affect the operation of the refrigerator. If the equipment is operated in conditions of high temperatures or high humidity, insufficient or excessive refrigerant consumption may lead to a decrease in cooling efficiency or overheating of the components.

The 3rd factor. System load: Load conditions significantly affect the optimal amount of refrigerant. An overloaded system may require more refrigerant to maintain the set temperature, whereas poorly loaded systems may function normally even with a reduced amount of refrigerant.

The 4th factor. Performance control: Modern control systems allow you to automatically adjust the refrigerant supply depending on the operating conditions. This helps to minimize the negative impact of changes in mass flow on productivity.

Thus, the statement about the non-influence of the mass flow of refrigerant should be considered in the context of the specific characteristics of a particular refrigeration system and its operating conditions.

4.3. Environmental benefits (reduced pollution, reduced fuel consumption) and their quantitative environmental and lifecycle analysis.

The use of secondary energy resources for drying agricultural products is a promising area that allows reducing the negative impact on the environment and reducing the consumption of traditional fuels [20]. Let's consider the main environmental advantages of this approach from the point of view of Russian experience and scientific research.

The main environmental benefits of the introduction of dryers with heat pump refrigeration units:

1. Reducing greenhouse gas emissions. Traditional drying methods based on the burning of fossil fuels (coal, oil, gas) lead to significant emissions of carbon dioxide and other pollutants. The use of secondary energy resources can significantly reduce the amount of harmful emissions. For example, a study conducted by the staff of the St. Petersburg State Agrarian University showed that the use of exhaust flue gas heat from boiler plants of agro-industrial enterprises reduces CO_2 emissions by about 30% compared with the traditional method of drying grain crops [21].

2. Saving fuel resources. The use of secondary heat from technological processes (for example, the use of exhaust steam, hot gases, or industrial wastewater) can significantly save fuel. According to

the Research Institute of Energy of the Ministry of Agriculture of Russia, the savings of natural gas during grain drying using thermal energy waste disposal technologies reach 20-30% [22].

3. Improving the energy efficiency of production. Secondary heat is a free resource available almost everywhere in the food industry, processing of raw materials and the agricultural sector. This helps to increase the energy efficiency of the enterprise and reduce production costs. Research conducted by the staff of the All-Russian Scientific Research Institute of Agricultural Electrification has shown that the introduction of fruit and vegetable drying technology using biogas plants reduces electricity consumption by 40%, while reducing energy costs.

4. Minimizing the impact on ecosystems. Replacing the traditional drying method with environmentally friendly technologies makes it possible to minimize the degradation of natural ecosystems caused by air and water pollutants. The use of low-temperature treatment methods using thermal radiation or infrared rays prevents the formation of carcinogens and mutagens characteristic of high-temperature burning .

Thus, the active introduction of secondary energy resources into the drying process of agricultural products has significant potential to improve the environmental situation in the regions and reduce the carbon footprint of the agricultural sector of the Russian economy [23].

4.4. Integration of wind turbine — theoretical and practical issues

The integration of a wind turbine into the process of drying agricultural products is a promising direction that significantly reduces energy consumption and increases production efficiency. Wind energy has a number of advantages over traditional energy sources, including environmental friendliness and the availability of renewable resources [24].

To analyze the feasibility of the proposed concept, we will consider the main factors:

The 1st factor. Energy potential. Using wind allows you to get energy almost free of charge after installing the equipment. The assessment of the energy potential of the region should be carried out taking into account the average wind speed and the duration of wind periods.

The 2nd factor. Technical specifications. The choice of the type of wind turbine depends on the specific operating conditions. It is necessary to take into account the power, reliability of the structure and resistance to external influences [25].

The 3rd factor. Economic feasibility. The calculation of the payback period for investments in the installation of a wind turbine includes an assessment of the cost of equipment, installation work and operating costs [26].

An analysis of data on the prevailing wind directions in cities located on the territory of the Russian Federation shows that there is a real possibility of effectively using a wind turbine to generate electric energy that ensures the operation of dryers with a heat pump refrigeration unit [27].

Connection with basic thermodynamic research.

Thermodynamics plays a key role in understanding heat transfer processes and energy conversion efficiency. The integration of a wind turbine requires consideration of heat losses and optimization of the thermal balance of the system.

Basic thermodynamic principles:

1. The law of conservation of energy (the first principle of thermodynamics).

2. Entropy and the direction of processes (the second principle of thermodynamics).

Thus, the integration of a wind turbine into the drying system of agricultural products seems to be a technically feasible and economically profitable project that ensures the sustainable development of the agro-industrial sector.

Analysis of the feasibility of a proposal to integrate a wind turbine in the drying of agricultural products and the relationship with basic thermodynamic research [27].

The integration of a wind turbine into the process of drying agricultural products is a promising direction for the development of environmentally sustainable technologies. The use of renewable energy sources can reduce energy costs and reduce the carbon footprint of agricultural production. Let's look at the main aspects of this approach and provide links to relevant scientific publications.

The main advantages of wind energy integration:

1. Renewable: The wind resource is an unlimited source of energy available almost everywhere.

2. Ecological cleanliness: No emissions of greenhouse gases and harmful substances into the atmosphere.

3. Cost-effective: After the system is installed, energy costs are minimal.

4. Energy independence: The ability to independently provide energy for drying processes, especially important for remote regions.

The thermodynamic basis of the drying process is to remove moisture from the product by evaporation of water.

Drying efficiency depends on many factors, including air temperature, humidity, air flow velocity, and the characteristics of the material itself. The most important aspects are thermal processes and the transfer of heat and mass.

Key principles and dependencies of the drying process:

1. The law of conservation of energy: $\Delta H=Q+W$, where ΔH is the enthalpy change, Q is the heat transferred to the product, and W is work (wind energy).

2. Heat transfer equation: $q=hA\Delta T$, where h is the heat transfer coefficient, A is the contact surface area, and ΔT is the temperature difference.

3. Dynamic moisture balance: achieving an optimal state in which further moisture loss slows down.

Connection with thermodynamic research

The use of wind turbines helps to ensure a stable flow of heated air, speeding up the process of moisture evaporation. It is important to take into account the thermodynamic efficiency of the system, including the energy balance and the efficiency of converting mechanical wind energy into thermal energy for heating the air. The general principles of heat treatment of food, including the role of ventilation and temperature control were considered [28]. The possibilities of increasing the energy efficiency of crop drying processes through integrated solutions were analyzed [29]. Specific examples of the implementation of wind turbine systems in the agro-industrial complexes of China were also presented [30]. Thus, the integration of wind turbines to provide energy supply for drying processes has significant prospects due to its environmental friendliness and cost-effectiveness. For

successful implementation, careful calculations and optimization of technological parameters are necessary, taking into account the specifics of each specific farm.

4.5. Discussion of limitations, uncertainties, or potential drawbacks of the proposed system.

A convective drying system using a heat pump refrigeration unit has a number of advantages due to its energy efficiency and environmental friendliness, but it also has a number of limitations, uncertainties and potential disadvantages [31].

Limitations when using a convective drying system with a heat pump refrigeration unit:

1. Dependence on ambient temperature: The efficiency of the heat pump decreases at low ambient temperatures, which limits the use of the system in regions with a cold climate.

2. Energy consumption for maintaining low humidity: In order to maintain an optimal humidity level inside the drying chamber, additional energy consumption is required for the operation of the compressor and fans.

Despite the high energy efficiency of heat pumps, the processes of dehumidification and condensation of moisture require additional energy, especially in systems with high quality requirements for the dried product.

3. Equipment cost: Heat pump systems often require significant capital investments, which increases the initial cost of implementing the technology. The system requires significant capital investments, including the installation of heat exchangers, compressors, and process control automation. These initial costs can be a barrier to widespread adoption of the technology in small businesses [32].

4. The need for qualified maintenance: The complexity of the design and the need for regular maintenance increase the operating costs and qualification requirements of personnel.

Uncertainties when using a convective drying system with a heat pump refrigeration unit:

1. Lack of standardized methods for calculating efficiency: Despite the development of technology, there are still no generally accepted methods for evaluating the energy efficiency of such installations, which makes it difficult to compare different models and choose the optimal configuration.

2. There is insufficient research on the long-term reliability of components: Although heat pumps are widely used, specific studies on the durability of individual elements (e.g. heat exchangers, pumps) under operating conditions have not been sufficiently studied. The complexity of the design of heat pump installations increases the likelihood of breakdowns and the need for regular maintenance. Insufficient reliability of components can negatively affect the performance of the entire system.

3. Prospects for the development of materials: Modern advances in materials science make it possible to create new types of thermal insulation coatings and improved structural solutions, however, additional research is needed on the impact of new materials on the efficiency and durability of equipment [33].

4. Optimization of drying modes. Choosing the optimal temperature and time parameters of the processes is a difficult task, since the products have different characteristics of moisture and

thermal conductivity. Erroneous modes can lead to a deterioration in product quality or an increase in energy consumption.

Potential disadvantages of the proposed system:

1. Problems with freon disposal: The use of refrigerants (freons) creates a risk of environmental pollution, especially if the equipment is improperly disposed of. It is important to follow strict rules for handling such substances.

2. The inability to quickly change the operating modes: Due to the design features of heat pumps, it is difficult to quickly change the operating mode of the system, which reduces the flexibility of controlling the drying process.

3. The possibility of condensation: During the operation of the installation, there may be a risk of condensation on the surface of the products, which requires additional quality control and timely cleaning of the chambers [34].

4. High cost of electricity. Even though heat pumps are economical, high electricity tariffs can significantly increase the operating costs of an enterprise. The cost of thermal energy production should be compared with the possibilities of alternative drying methods [35].

5. Limited performance. Convective dryers with heat pumps have a limited capacity compared to traditional direct air heating methods. Therefore, such systems are less effective in mass production of large volumes of products [36].

Thus, despite the advantages, a convective drying system using a heat pump has limitations, uncertainties and risks that must be taken into account when designing and operating such equipment.

4.6. Discussion on process suitability, product quality impact, or scalability

A convective dryer with a heat pump refrigeration unit is an innovative food processing technology that significantly improves the efficiency and environmental friendliness of raw material dewatering processes. Let's consider the principle of its operation, the impact on product quality and the prospects for scaling production.

A convective dryer is an equipment that is designed to remove moisture from a product by forcibly circulating heated air around the material being processed. The drying process in such dryers is as follows:

1. The raw materials are placed inside the dryer chamber, equipped with fans and heating elements.

2. Heaters ensure that the temperature inside the chamber rises to a preset level.

3. The air flows are evenly distributed throughout the volume, accelerating the evaporation of moisture.

4. An environmental parameter monitoring system is used to maintain optimal humidity and temperature.

However, the classical method has a number of disadvantages: high energy consumption, long drying time and possible deterioration of the quality of the final product due to high temperatures. To solve these problems, a heat pump refrigeration unit is used. Its main task is to save energy by reusing the heat generated by the cooling system.

The dryer with a heat pump refrigeration unit functions as follows:

1. The refrigeration unit extracts heat from the environment (for example, indoor air).

2. The resulting heat is sent back to the dryer chamber, maintaining optimal conditions for fast and uniform drying of the product.

3. This reduces electricity consumption and space heating costs.

Proof of the suitability of the process.

Let's look at the key performance indicators of the technology:

1. Saving energy resources.

Using a heat pump reduces energy consumption by about 30%-50% compared to traditional methods. For example, the power consumption of a conventional electric heater is about 8-10 kW/h, while a heat pump provides a similar effect with a power of only 2-3 kW/h.

2. Product quality improvement. With traditional drying methods, vegetables, fruits and cereals are often subjected to overheating, which worsens the taste characteristics and reduces the nutritional value. The use of a dryer with a heat pump refrigeration unit allows you to keep the temperature below the critical point (usually less than 60 °C). This preserves the vitamins, minerals, and aromatics of the feedstock.

3. Environmental safety. The absence of harmful emissions into the atmosphere makes the process environmentally friendly and safe for the health of the company's employees.

4. Production scalability. The technology has the potential to expand production capacities due to the modular principle of equipment construction. It is possible to organize serial production of standard modules of various capacities, which will allow you to quickly adapt to the growing demand for products. In addition, the use of digital technologies for monitoring the condition of equipment and process control makes it possible to automate all stages of the production cycle, including quality control of finished products.

Thus, the use of a heat pump is a cost-effective solution for food industry manufacturers.

Thus, the use of a convective dryer with a heat pump refrigeration unit demonstrates a high degree of readiness for industrial implementation. It ensures the economical production of high-quality products while minimizing the negative impact on the environment. This technology opens up new opportunities for the development of the agricultural processing industry and will increase the competitiveness of domestic enterprises.

4.7. Alternative refrigerants, modern heat pump dryers and existing technologies

Refrigerants are substances used in cooling and air conditioning systems to transfer heat. The main types of refrigerants:

1. Freons. Freons were widely used earlier due to their effectiveness and low toxicity. However, it turned out that many freons destroy the Earth's ozone layer, contributing to global warming. For this reason, the use of many types of freons has been restricted by the international agreement of the Montreal Protocol.

Advantages of using freons:

-heat exchange efficiency;

- low corrosion activity.

Disadvantages of using freons:

- destruction of the ozone layer;

- strong influence on climate (greenhouse effect).

2. Ammonia (Nh_3). Ammonia is one of the most common natural refrigerants. It is used in large industrial installations, refrigerators and air conditioners.
Advantages of using ammonia:

- high efficiency of heat transfer;

- zero impact on ozone depletion;

- availability and low cost of production.

Disadvantages of using ammonia:

- toxicity and leakage hazard;

- corrosion of certain metals.

3. Hydrofluorocarbons (HFCs). Hydrofluorocarbons (HFCs) were introduced as a replacement for traditional freons. They are less dangerous to the ozone layer, but some types of HFCs have a significant greenhouse effect.

Advantages of using hydrofluorocarbons:

- no effect on the ozone layer;

- wide availability and ease of maintenance of the equipment.

Disadvantages of using hydrofluorocarbons:

- Significant impact on climate change;

- the cost is higher than traditional refrigerants.

4. Natural refrigerants (CO_2, H_2O, air). These refrigerants have low or zero ozone depletion capacity and minimal climate impact.

Advantages of using natural refrigerants

- environmental safety;

- renewable resources.

Disadvantages of using natural refrigerants:

- limited performance.

- the need for specialized technologies and materials.

Advantages of heat pump dryers over traditional drying methods.

Drying of food, wood, grain and other materials is of great importance in industry and agriculture. Traditional drying methods such as convective hot air drying, infrared drying, and microwave drying often require significant energy expenditure and result in loss of product quality.

Modern technologies based on the use of a heat pump offer a number of advantages:

1. Energy saving. The heat pump is able to extract energy from the environment (air, water or earth), significantly reducing electricity costs compared to conventional heating elements. An example of calculating savings:

Let's say the performance coefficient (COP) of a heat pump is 4. This means that every kilowatt of electrical energy invested is converted into 4 kilowatts of thermal power. Thus, energy costs are reduced by about 75% compared to conventional electric heating.

2. Maintaining stable temperature and humidity. Heat pump-based systems allow precise control of temperature and humidity inside the drying chamber, ensuring uniform heat distribution and preventing overheating of the material. Temperature control is important to preserve the beneficial properties of the dried product. For example, high temperatures can lead to the destruction of vitamins and nutrients in food.

3. Increased energy efficiency. Due to the possibility of reuse of waste heat, heat pump-based systems provide significant energy savings. The use of re-extracted heat makes it possible to reduce the consumption of primary energy carriers, which reduces the operating costs of the enterprise.

4. Environmental friendliness. The use of low-toxic and environmentally friendly refrigerants helps to reduce the negative impact on the environment. Traditional drying methods often use fossil fuels, which leads to emissions of CO_2 and other pollutants. The use of heat pumps helps to reduce the carbon footprint of enterprises.

5. Durability and reliability. Heat pump-based installations are characterized by high service life and reliable operation. Proper maintenance ensures long-term operation without significant loss of productivity. Modern models of heat pumps are designed for a service life of about 15-20 years, which is comparable to similar indicators of traditional equipment, but at lower operating costs.

Thus, the use of heat pumps in drying technologies represents a significant potential for increasing energy efficiency, improving product quality and reducing the burden on the environment.

Comparison of refrigerants, modern dryers with a heat pump or with other existing technologies.

Refrigerants.

Modern refrigerants are classified according to the following criteria:

1. Environmental safety: the level of impact on the ozone layer (ODP), global warming potential (GWP).

2. Cooling efficiency: thermal conductivity, heat capacity, viscosity.

3. Compatibility with equipment materials: corrosion resistance, oil solubility.

The most common types of refrigerants:

1. HFC refrigerants (HFC): widely used due to their low toxicity and lack of impact on the ozone layer. Examples: R-134a, R-410A.

2. Natural refrigerants: ammonia (R-717), carbon dioxide (R-744). They are environmentally friendly, however, they require special operating conditions.
3. New generation Hydrofluorocarbons (HFO): new developments with low levels of ODP and GWP. Example: R-1234yf.

If we compare the three types of refrigerants in terms of their cooling efficiency, HFC refrigerants (HFC) R-134a occupy the second place after new generation hydrofluorocarbons (HFO) R-1234yf. Natural refrigerants: ammonia (R-717), carbon dioxide (R-744) have the worst cooling efficiency.

Therefore, HFC refrigerant (HFC) R-134a was chosen by the authors of the article as the refrigerant for dryers with a heat pump.

Modern dryers with heat pumps.

Heat pump refrigeration dryers are an energy efficient technology for drying materials based on the transfer of heat from the environment to the drying chamber.

The main advantages of the heat pump include reduced energy consumption and improved quality of dried products.

The main components of the system:

1. Compressor.

2. The capacitor.

3. The evaporator.

4. Expansion valve.

Advantages of using a heat pump over traditional drying methods:

1. Energy savings of up to 50% compared to conventional electric heaters.

2. Maintaining stable temperature and humidity inside the chamber.

3. Minimal environmental impact due to the efficient use of renewable resources.

In addition to heat pump technologies, there are also traditional drying methods:

1. Convective drying: The most common method using hot air to remove moisture from the material.

2. Infrared drying: using infrared radiation to heat the surface of the product. 3. Microwave drying: the use of microwave energy for rapid dehydration.

4. Radio frequency drying: material treatment by high frequency electromagnetic waves.

Each technology has its own characteristics and applications. The choice of method depends on the type of material being processed, the required level of productivity, and economic factors.

When choosing the optimal solution, it is important to take into account the characteristics of specific production conditions, product quality requirements and the economic performance of the project. The use of new environmentally friendly refrigerants minimizes the negative impact on the environment, and modern drying units with heat pumps significantly reduce energy costs.

5. Conclusions

In the thermal *Ts*-diagram for R134a freon, a thermodynamic cycle of operation of a convective drying unit with a compression heat pump refrigeration unit was designed. For the convective drying unit proposed by the authors, which works in conjunction with a compression heat pump refrigeration unit, a design calculation based on algebraic equations was carried out. It was assumed that the mass second consumption of R134a freon circulating in a compression heat pump refrigeration unit is M = 0.1 kg/s (0.22 lb/s).

The thermodynamic parameters of the state at the characteristic points of the reverse cycle are determined using the thermal *Ts*-diagram for R134a freon. It was found that the total cooling capacity is Q_0 = 11.9 kW (11.279 Btu/s), and the value of the specific cycle performance is 28 kJ/kg (12.0378 Btu/lb). The theoretical drive power of the compressor of a thermal refrigerating unit is N = 2.8 kW (2.654 Btu/s). It is established that the refrigeration coefficient is ε = 4.25, and the heating coefficient is ϕ = 5.25.

The analysis of the thermodynamic cycle of a compression heat pump refrigeration unit and the calculation performed for R134a freon shows that the selected refrigerant fully provides all modes of operation of the convective dryer. It was found that a change in the mass second flow rate of R134a freon does not affect the values of the refrigeration (ε) and heating (ϕ) coefficients. The specific values of the refrigeration and heating coefficients depend only on the nature of the refrigerant circulating in the compression heat pump refrigeration unit. The main advantage of a heat pump refrigeration unit for drying is the possibility of returning the latent heat of steam obtained from the moisture of the dried product by reverse condensation of water vapor contained in the exhaust drying agent (air).

It has been found that for optimal operation of convective dryers with a compression heat pump refrigeration unit, the critical temperature of the refrigerant (R134a freon) has to be significantly higher than the temperature of the drying agent (heated air) at a not very high critical pressure. The presented convective dryer with a compression heat pump refrigeration unit operates

on a closed cycle, which significantly reduces power consumption due to the lack of need for constant supply of portions of outside air to the dryer and its heating to a preset temperature using an electric heater. The convective dryer design proposed by the authors will significantly reduce the consumption of organic fuels, reduce environmental pollution and provide an opportunity to prepare thermal energy in sufficient quantities for the needs of consumers. A convective dryer with a compression heat pump refrigeration unit can be used for drying fruits, vegetables and cereals. Since it is necessary to constantly spend work on the compressor drive of a heat pump refrigeration unit, in order to increase the efficiency of the power plant, a wind turbine can be included into the design of the presented convective dryer, which will produce electrical energy using a generator. It has been established that for every 1 kW (0.9478 Btu/s) of electric energy paid, it will receive 4.25 kW (4.0282 Btu/s) of heat transfer.

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Conflict of Interest Statement
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Author Contributions Statement
Roman A. Usenkov conceptualized and designed the study, supervised the project, and reviewed the manuscript. Svetlana Ya. Kokhanova conducted the experiments and data analysis. Maxim V. Trushin contributed to data interpretation and wrote the initial draft of the manuscript. All authors contributed to manuscript revision, read, and approved the final version.

Data Availability Statement
All data generated or analyzed during this study are included in this published article. Additional datasets are available from the corresponding author upon reasonable request. Where applicable, publicly available datasets used in the study are cited in the references.

Ethics Statement
This study was conducted in accordance with the ethical standards of the institutional and/or national research committee. Ethical approval was obtained where required, and informed consent was obtained from all participants involved in the research.

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