Phase transitions in food production technologies

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Abstract

Introduction. The article deals with information about the general state of technologies for the utilization of secondary energy resources and environmental resources.

Materials and methods. Energy-consuming processes are investigated from the point of view of using their potentials as isoenthalpy in malt dryers, fermenters, heat pumps and vacuum dryers in their classical design. Research methods are based on the principles of technical thermodynamics. The combination of these objects concerns the possibility of creating closed energy-material circuits on their basis by supplementing them with compensatory processes.

Results and discussion. The analysis of isoenthalpy drying processes led to the conclusion that it is expedient to keep the total potential of the vapor-gas mixture in closed circuit, but with the feature that the drying potential of the medium will be renewable. Since the extraction of the vapor fraction is possible only through its condensation, which is carried out using a heat pump, energy potential is returned in it to the gas flow during its passing through the condenser.

It is shown that such a system implements the tasks of drying the grain mass, transporting the vapor-gas mixture, drying the gas fraction and returning energy potential to it. The heat pump circuit in this system plays a regulatory role in relation to the steam-gas mixture circuit, and the compensation process is assigned to the heat pump compressor.

It was shown that the thermodynamic properties of phase transitions correspond to the isobaric-isothermal process and this has at least two advantages from the point of view of the interests of energy recovery and regeneration. Firstly, as a result of the phase transition, the enthalpy of the vapor fraction is approximately 5 times higher than the enthalpy of the liquid fraction. Secondly, the temperature of the steam or gas phase can be changed by mechanical or thermal compression, including for changing temperatures of the phase transitions. The consequence of such transformations is the ability to minimize the cost of primary energy resources for evaporation processes.

Conclusions. Partially hydrolyzed protein samples had higher protein content, lighter color, lower degree of denaturation and better functional properties compared to the traditional protein isolates.

Introduction

Prospects for the restoration of low-temperature thermal resources with the latest technical capabilities are widely reflected in the general provisions of thermodynamics, and in solving individual technological problems [1, 3]. The dynamics of the use of heat pumps is achieving the levels of industries [5]. However, in each case the problem of phase transitions of working media at the level of parameters of the spent thermal energy and temperature modes of heat streams at the exit from the system should be solved [6].

In each case the problem of phase transitions of working media at the level of parameters of the spent thermal energy and temperature modes of heat streams at the exit from the system should be solved. The total potential of energy resources to be recovered in the industries of the EU is 7% of the total spent heat resource [3] with the ability to reach source temperatures up to 150 °C. Authors [7] provided information on the creation of a cascade heat pump with a capacity of 20 kW with propane in the low-temperature cycle and butane in the high-temperature cycle with a range of heat flux recovery from 30 °C to 115 °C.

The creation of systems for the utilization of secondary energy resources required an initial analysis in terms of assessing the possibilities of local transformation of thermal waste and the optimal use or connection to existing power systems. The combination of heat pump, heat transfer system and heat storage system can meet the needs at the relevant time scale, spatial coordinates and energy level. In the publication [8] it was proved that the logical addition of heat flow transport systems were heat pipes.

The technical limitation of the implementation of significant temperature differences in phase transitions forced the use of systems with three independent cycles [9]. Comparison of such triplex systems of heat pumps with single-circuit analogues showed the advantage of the first ones.

In the study [5] the use of secondary energy resources was associated with the prospects of reducing the risks of global warming, the concept of industrial waste heat, potential sources of the latter were defined, available for disposal resources were highlighted, heat pumps, heat exchangers, power cycles, transportation systems were illustrated.

The study [10] presented options for heat recovery of heat pumps for drying equipment for the food industry. Heating of air as a drying agent by heat recovery was carried out using ‘air-to-air’ heat exchangers and heat pumps up to 200 °C. The temperature of wasted air was 76 °C with a dew point of 38.5 °C. At the evaporation temperature of 25–30 °C, up to 40% of the air heating load was provided with a 20% reduction in energy cost. The transcritical cycle with dehumidification of wasted air at the constant temperature and heating of the input air in the supercritical area is thermodynamically good for the drying process.

Another direction of implementation of the fresh air dehumidification system concerned the use of the heat pump with the heat exchanger covered with the dehumidifier [11]. This treatment was due to the fact that dehydration with the transition to the dew point led to increased levels of electricity consumption in traditional air conditioning. The proposed system was recognized as effective for the treatment of air with high relative humidity.

Article [12] dealt with exergetic analysis of heat pumps for simultaneous generation of flows with elevated temperature and cooled flows.

The combination of low-temperature and solar energy potentials was estimated to have significant potential for different applications. Publication [13] summarized various aspects of this technology, including system configurations, performance optimization, simulation models, and various applications.

Analysis of the course of a significant number of food technology processes led to the conclusion that it was possible to complete them with components which transform the system to the levels of closed circulation circuits. This applied to the processes of drying, concentration of solutions, aeration of culture media, germination of grain areas and determined the relevance of the research topic.

The purpose of the study was to assess the prospects for the implementation of proposals for the use of secondary energy resources in existing systems by supplementing them to the levels of closed energy circuits.

Materials and methods

Materials Energy-consuming processes are investigated from the point of view of using their potentials as isoenthalpy in malt dryers, fermenters, heat pumps and vacuum dryers in their classical design [1, 2]. The combination of these objects concerns the possibility of creating closed energy-material circuits on their basis by supplementing them with compensatory processes [1, 3, 4].

Methods. Research methods are based on the principles of technical thermodynamics.

Results and discussion

General provisions

Water and water vapor can be attributed to the most common working fluids and media in food technologies [1]. This is due to the fact that their physical and chemical properties correspond to the conditions of existence of the biological world, and are in sufficient quantities in the environment [2]. Water is quite cheap, non-aggressive to the materials of technological equipment and through phase transitions in the cycles of natural cycles restores its properties. However, the phase transitions of evaporation and condensation of water vapor are inherent in the majority of industries [3]. However, the list of used media is logically supplemented by other substances involved in refrigeration plants, heat pumps, in the production of alcohol, liquefied gases, in the processes of crystallization, drying. In this case, water often acts as the medium in which thermal, chemical, mass transfer or biochemical processes take place. It is obvious that such a set of possibilities for the application of known and not known yet properties is based on information in the form of the laws of physics, chemistry, thermodynamics.

According to its characteristics, water vapor is a typical representative of real working bodies (the presence of its own volume of molecules and the forces of interaction between them). Therefore, the application of the equation of state of ideal gases to water vapor is almost impossible [1], and engineering calculations are proposed to do using thermodynamic tables and entropy diagrams i-s and T-s, built on the basis of experimental data.

The processes of formation of the vapor fraction are isobaric-isothermal, so to determine the state of the system it was necessary to have information about the parameters of pressure p, temperature t and degree of dryness. In estimating secondary energy resources in thermodynamic systems, the relationship between the enthalpies of liquid and vapor fractions, the heat of vaporization and the values of entropies depending on the pressure and the corresponding temperature were important [1]. These ratios in a significant number of technological processes led to the possibility of recovery and regeneration of energy potentials. Such transformations are often based on the addition of steam, gas or steam-gas systems with mechanical or thermal energy [2].

Since in the isolated flow system the sum of all types of energy remained constant, the equation of energy balance of the system had the form [1]:

$$E_s = \Delta E_g + E_r \, , \tag{1}$$

where E_s i E_r –supplied and removed energy respectively, J; ΔE_g – energy gain of the system, J. In the elementary process [1], the energy balance equation is represented by the formula:

$$\dot{E}_s d\tau = dE_g + \dot{E}_r d\tau \, , \tag{2}$$

where $\dot{E}_s$ та $\dot{E}_r$ –the flows of supplied and removed energy respectively, W; dτ – elementary process time. For a stationary process within a unit of time we have:

$$\dot{E}_s = \dot{E}_r \, . \tag{3}$$

Transition to the balance of mass flows was made similarly:

$$\dot{m}_s = \dot{m}_r \, . \tag{4}$$

Double-circuit recuperative malt dryer

Conditions (1) – (4) corresponded to those processes which occurred in isolated or conditionally isolated thermodynamic systems of aeration of culture media of aerobic or anaerobic cultivation of microorganisms, germinated malt, mixing streams, heating-cooling. Thus, the drying of malt or other grain mass occurred due to the interaction of the latter with the drying agent, the result of which was the redistribution of moisture and energy potentials [1, 2]. However, the total energy potential remained constant, which defined the drying process as isopotential. The direction of the material flow in the direction from the grain to the drying agent and the recognition of the process as isopotential led to the conclusion about the feasibility of using system with regeneration of the drying agent by removing the vapor phase and parallel recovery of energy potential with increasing temperature. It ws obvious that the technical possibility of extracting the vapor fraction was associated with its condensation due to cooling of the gas or steam-air mixture. This meant that the energy potential of the condensing heat must be absorbed by the refrigerant of the heat pump. Having been removed from the drying agent condensate was removed from the system, and the low-potential heat energy flow obtained in the evaporator was transformed in the heat pump circuit into the high-potential one, which was transferred to the drying agent in the latter condenser (Figure 1).

Regenerated in this way in terms of energy and material indicators drying agent moved in a closed circuit A with the corresponding transformations in the circuit B of the heat pump. The initial power supply of the system was due to the heater 3, and in steady state – due to the compressor of the heat pump and the potential of the drying agent. The role of the energy-mass regulator in the system was performed by the heat pump circuit, and the evaporator of the latter was also a condenser of the circuit A of the drying agent.

The dryer itself was the evaporator in circuit A.

A common feature of both circuits was the presence of phase transitions in the modes of evaporation and condensation, due to which the restoration of driving factors was achieved in accordance with the second law of thermodynamics.

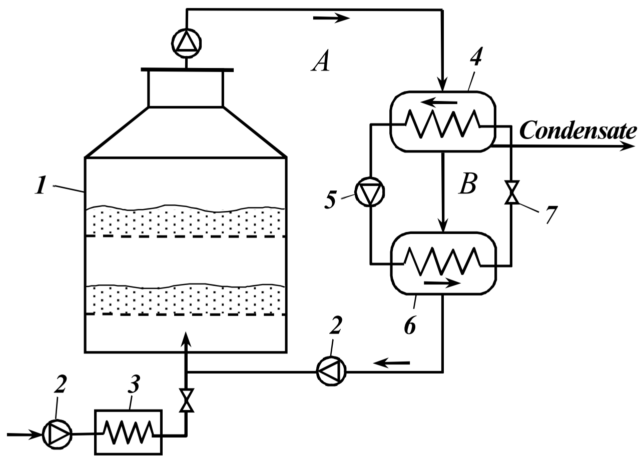

Figure 1. The scheme of the device for drying malt:
A – contour of the drying agent; B – contour of thermal agent; 1 – dryer; 2 – fans; 3 – heater of drying agent; 4 – heat pump evaporator and condenser of steam of the drying agent; 5 – compressor; 6 – condenser of the heat pump; 7 – control valve

Thus, the compression of gas by the compressor led to an increase in temperature due to the mechanical reduction of the volume with a constant value of entropy. In the reverse process, the expansion of the compressed gas compensated energy costs. This feature in the form of adiabatic processes was used in refrigeration cycles and cycles of heat pumps with a super-important effect to change the temperature of the phase transitions. The latter opened the possibility of efficient mass and energy-intensive processes with technological medium and environment, including due to phase transitions with a high value of heat output and heat transfer coefficients. The presence of a phase transition with the formation of vapor or gas phase meant the creation of powerful energy flows, which were analogous to energy-saturated areas like a heat pipe. In this case, the circuit A was closed and met the requirements of the process, and the compensation process in its structure corresponded to a set of processes of condensation of the vapor phase and subsequent heating of the drying agent. In the heat pump circuit, the compressor and the control valve corresponded to the compensation process in its execution. The presence of the latter in the circuit of the heat pump as in an isolated system allowed to create and update temperature differences in the evaporator and condenser, ensuring that the system was in terms of heat transfer in an unbalanced state. The heat flux perceived by the thermodynamic refrigerant from the medium of circuit A was replenished by the potential of the compressor. It is known that the most efficient reverse cycle is the Carnot cycle.

In the technological process corresponding to the circuit A, there were thermodynamic processes of condensation of the vapor phase with appropriate cooling and subsequent heating of the gaseous part of the medium. The performance of both tasks was entrusted to the heat pump.

The next process in circuit A was the evaporation of the wet fraction. Thus in circuit A there were operations of phase transitions, as well as in circuit B of the heat pump. However, it was impossible to organize the work of the first on the basis of thermodynamic principles of the second due to the combined vapor-gas medium and the peculiarities of the interaction of the drying agent and the humid medium, which are shown in diagram I-d. However, the isoenthalpy nature of the latter determined the possibility and feasibility of creating recovery modes based on closed circuits in parallel and synchronized material and energy flows. The material flow of circuit A in the area between the evaporator of the heat pump and the dryer was represented by air, and in the dryer and to the evaporator – by a vapor-gas mixture. In the evaporator of the heat pump, which simultaneously acted as a steam condenser of the drying agent, the interaction between which and the thermodynamic agent of the heat pump, the condensation of the vapor phase was completed and the condensate was removed from the circuit.

Condensation of the vapor phase of the drying agent in the evaporator of the heat pump was accompanied by active heat transfer of the coolant to the circuit B, which in the form of vapor phase entered the compressor, compressed with increasing temperature and energy potential, and with the transition to the condenser 6 of the heat pump due to its condensation the return of the energy potential of the flow of drying agent was carried out. Restoration of the drying properties of the latter and its initial thermodynamic parameters meant the creation of a second closed energy circuit based on the circuit of the heat pump. An important combination of such a double closed-loop system was the technical ability to perform material flow processing in a continuous mode, provided the required input initial thermodynamic parameters.

The closed circuit B of the heat pump was arranged on the basis of the classical Carnot reverse cycle, in which the compensation process was represented by mechanical compression of the vapor phase. Compression itself was a prerequisite for the creation of driving factors of heat transfer in combination with the throttling of the refrigerant. Synchronization of the corresponding processes in the circuits A and B was reflected in the sequence of their execution in Figure 2.

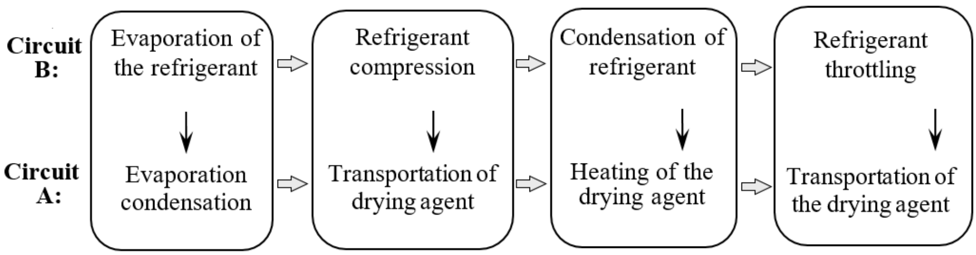

Figure 2. Synchronization of processes in the circuits A and B from Figure 1

The absence of compression in the circuit A was compensated by the heating of the drying agent and this change will be conventionally considered to be analogous to thermal compression.

Parallel synchronous operation of both circuits ensured the retention of energy potential in the system, which meant the possibility of full use of the features of drying processes as isoenthalpy.

Fermentation apparatus with distillation function

A significant number of media in food technologies has relatively small temperatures, which allows them to be classified as low-potential [2, 5]. Methods of converting processes to high-potential include mechanical or thermal compression of steam, gas or steam-gas media [1, 7]. In most cases [10], such transformations are used for recuperative transformations, but in parallel with them, purely technological problems are solved.
An example of such a dual purpose relates to the patent of Ukraine for the invention 107407 "Fermenting apparatus". Its schematic representation is shown in Figure 3.

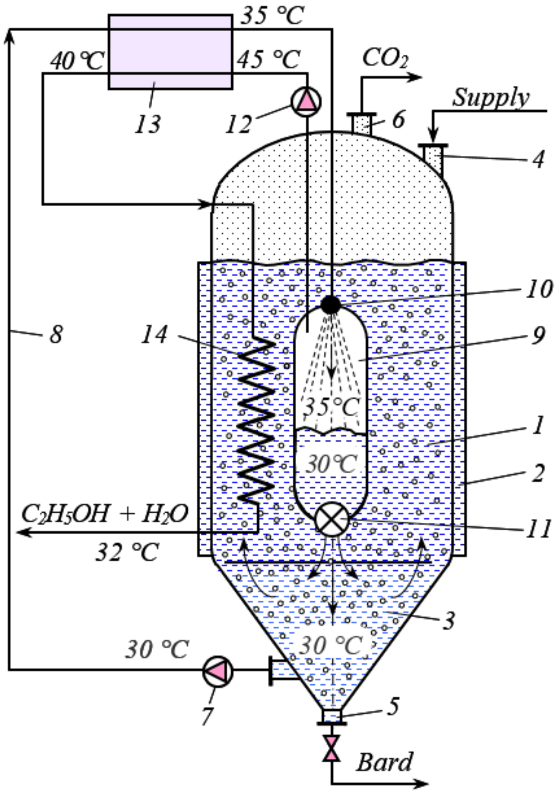

Figure 3. Scheme of the fermenter with a recuperative system of alcohol extraction

The unit consists of a cylindrical body 1 with a cooling jacket 2, a conical bottom 3, supply pipes 4 and discharge of fermented medium 5, safety valve 6, medium circuit with pump 7, pipeline 8, vacuum chamber 9 with dispersing head 10 and sluice gate with a sealed actuator 11, a vacuum circuit with a vacuum pump 12, a heat exchanger-recuperator 13 of liquid and steam-gas flows and a condenser 14 of the steam mixture.

The invention is based on the task of combining the processes of fermentation and extraction of alcohol, reducing the osmotic pressure in the medium, increasing the average fermentation rate of sugars and productivity of the fermentation process, reducing energy consumption to ensure fermentation and subsequent distillation.

To stabilize the concentration of alcohol at a given minimum level, the circuit of the medium with the pump 7, the pipeline 8, the vacuum chamber 9 with the dispersing head 10 and the sluice gate with the sealed actuator 11 was turned on and the medium was provided into the vacuum chamber 9, in which the liquid phase was dispersed, the alcohol evaporated, and the sluice gate with a sealed actuator removed the liquid fraction into the medium of the fermentation apparatus. Due to the reduction of the pressure in the vacuum chamber to 70 mm Hg boiling and evaporation of alcohol were achieved at a temperature of 30 °C and the formation of a water-alcohol mixture with an alcohol concentration of 50–60% occured. Compression of this mixture by a vacuum pump 12 led to an increase in temperature and pressure and it was provided to the heat exchanger-recuperator 13 of the liquid and vapor stream. The transfer of the latter to the condenser 14 provided complete condensation of the water-alcohol mixture and the return of thermal energy to the fermentation medium.

The condensed mixture was provided to the distillation and due to the high concentration of alcohol in it the energy saving effect of the system was achieved.

In connection with the latter, it is worth emphasizing that the double energy result of the system was due to the fact that the stabilization of the medium temperature at the nominal level was provided by the removal of fermentation heat, which in this case was involved in the vacuum distillation process. Due to the variable pressures of vapor-liquid mixtures, thermodynamic parameters of phase transitions with a temperature close to the nominal one for yeast with satisfactory differences on the heat exchange surfaces were achieved. In such a system, the external heat dissipation, which is presented in the classical schemes of fermenters [2, 9] and is an additional energy load, in this case was equivalent to the distillation potential and logically complemented the overall positive of the system. The sequence of processes in this system had the form:

Vacuum evaporation with enrichment of the vapor phase with alcohol ⇒ Compression of steam-water mixture ⇒ Recuperative cooling of steam-water mixture ⇒ Condensation of steam-water mixture

An important technological result in this case was the stabilization of osmotic pressures in the fermentation medium at the nominal level due to the limitation of alcohol concentrations due to changes in physical pressures in certain parts of the system. In addition, this patent did not contain information regarding the solubility of carbon dioxide synthesized in the system. Its concentration reached saturation and this was accompanied by additional mass transfer resistance on the phase separation surface. The reduction of the pressure in the vacuum chamber in accordance with Henry's law was accompanied by a corresponding share of desaturation with subsequent removal of CO_2 and additional positive effects on the system.

Thus, the combination in the system of phase transitions within the given thermodynamic parameters was accompanied by the following provisions:

- The main technological result of reduction and stabilization of osmotic pressure at the nominal level;
- Use of thermal fermentation potential for distillation;
- Regenerative support of the general energy potential of the system;
- No energy costs for cooling the fermented medium;
- Desaturation of the liquid phase of the medium.

Earlier it was noted that the energy costs of compensation processes were determined by temperature differences in isothermal phase transition processes [11]. That is why the efficiency of heat pumps largely depended on the temperatures of the carriers of low-temperature potentials. At the same time, for use in thermodynamic cycles of ammonia or freons (CFCs), their condensation temperatures were also limited and amount to 35–40 °C [8]. Expansion of the thermodynamic range of use of heat pumps related to the patent of Ukraine for the invention 90919 (Figure 4) with the following formula: a heat pump consisting of series-connected compressor, condenser, control throttle and evaporator, which differs from the previous inventions by the fact that the condenser was made in the form of a sealed tanks with a heat transfer surface and equipped with an axial compressor and a hydraulic power shut-off valve.

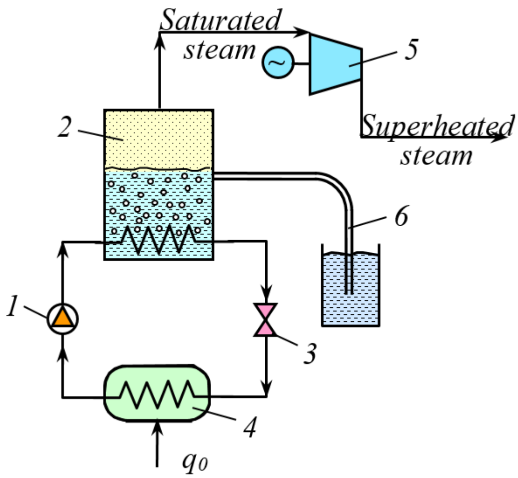

Figure 4. Heat pump circuit

The design of the condenser with its axial compressor and hydraulic shut-off valve made it possible to create a vacuum in its volume, boil the intermediate heat agent and generate its vapor, compress the latter and increase its temperature, which meant the transition of the intermediate heat agent to high potential. The hydraulic power shut-off valve maintained the nominal level of the intermediate heat agent (water).

The heat pump works as follows: compressor 1 sucks the refrigerant vapor from the evaporator 4, compresses it with increasing temperature and provides with new parameters to the condenser 2. Condensation of the refrigerant is carried out by removing the heat of condensation from it by the boiling intermediate heat agent. The boiling point of the latter is regulated by evacuating the system by an axial compressor 5, the compression of steam which increases its thermodynamic parameters to the level of high-potential ones. The level of the intermediate heat agent (water) in the condenser is regulated by the hydraulic shut-off valve 6. The condensed refrigerant in the throttle 3 reduces the pressure and enters the evaporator 4, completing the refrigeration cycle.

The following relations correspond to the specified set of processes:

$$q_c = q_0 + \ell; \quad q_n = q_c + \ell_{a.c.} = q_0 + \ell + \ell_{a.c.}, \tag{6}$$

where q_c – specific heat of condensation of a thermodynamic agent; q_0 – specific heat perceived by the thermal agent in the evaporator; ℓ – compressor operation; $\ell_{a.c.}$ – operation of the axial compressor.

The technical result related to the possibility of obtaining an intermediate thermal agent with high potential thermodynamic parameters.

Adding to technological complexes with phase transitions and the formation of a steam or gas structure can be considered an important indication of the feasibility of creating a recovery circuit [11, 12]. This was all the more important because under such conditions there were opportunities for additional variations in the effects on the technological parameters of the systems. Thus, the limitation of temperatures while maintaining the dynamics of the process allowed the drying of thermolabile products, to store vitamin complexes and biologically active substances under low pressure [13].

Such conditions are met by a continuous vacuum dryer (Ukrainian patent for invention 112880), a scheme of which is shown in Figure 5.

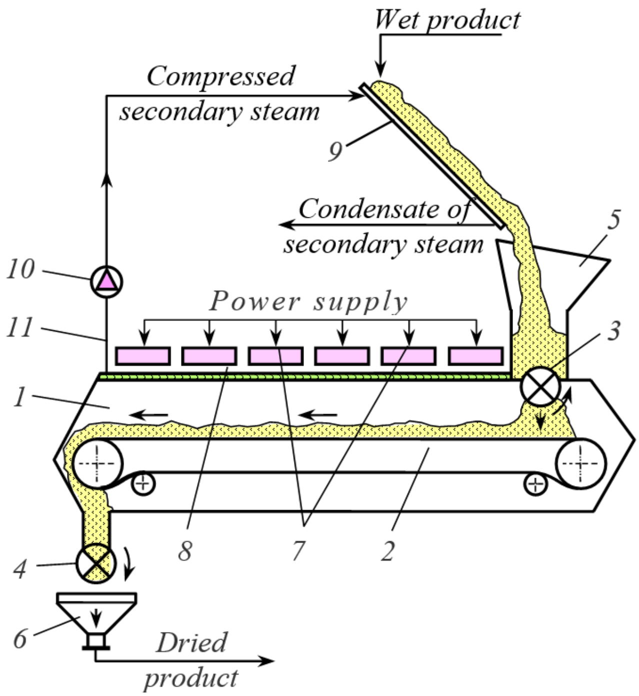

Figure 5. Scheme of a vacuum dryer of continuous action

According to the invention, the vacuum chamber is equipped with a belt conveyor with loading and unloading sluice gates with hoppers and energy-permeable screen, and the primary power supply system is made in the form of infrared radiation sources located above the energy-permeable screen, and supplemented by the circuit of secondary recuperative resources with a secondary steam pipeline, a vacuum pump and a conductive heating surface of the product, which leads to increased productivity, the implementation of a continuous process, stabilization of temperature conditions, preservation of biologically active substances.

The device works as follows: the wet product is provided to the surface 9 of the conductive heating, from which under the action of gravitational forces enters the loading hopper 5.

The product enters the belt of the conveyor 2 of the vacuum chamber 1 along the sluice gate 3. In the process of moving the belt, the product is irradiated through the energy-permeable screen 8 by infrared rays from sources 7.

When vacuuming the internal volume of the vacuum chamber by the vacuum pump 10, secondary steam (steam released from the product) is removed by pipeline 11. Compressed by the vacuum pump steam enters the surface of conductive heating, and the dried product is transferred from the belt of the conveyor to the sluice gate 4 by gravity, from which it is transferred to the unloading hopper 6, and is allocated for packaging or storage.

Conclusion

The thermodynamic properties of phase transitions corresponded to isobaric-isothermal processes, which from the point of view of the interests of energy recovery and regeneration had at least two advantages.

Firstly, as a result of the phase transition, the enthalpy of the vapor fraction was approximately 5 times higher than the enthalpy of the liquid. It was important that the generation and condensation of steam were characterized by the same heat of phase transitions.

Secondly, the temperature of the vapor or gas phase can be changed by mechanical or thermal compression, including to change the temperatures of the phase transitions. The latter opened up prospects for the implementation of several stage condensations and generations of steam fraction in the direction of decreasing and increasing temperatures and pressures of phase transitions. The ability to minimize the cost of primary energy resources for evaporation processes was the consequence of such transformations.

Energy-intensive drying processes, aeration of grain masses during germination, culture media in the synthesis of microorganisms or their derivatives were evaluated as isoenthalpy, which meant the feasibility of creating closed energy circuits, as the hardware design of technological devices often had components at the level of heat pumps.

The initial energy potentials of the systems were represented by the components of secondary steam and condensate, and the combination of phase transitions with technological processes has prospects in the processes of drying, evaporation, aeration, anaerobic fermentation.

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