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DESIGNS OF DRYERS BASED ON COMBINATION OF VACUUM AND ATMOSPHERIC DRYING OF FOOD PRODUCTS

Abstract. Among the advanced food dehydration technology, heat pump drying is characterized by the simplicity of the dryer design and a high level of latent heat recovery. It has a number of advantages in relation to the quality of dried products and regulation of drying modes, so it is advisable to include a heat pump in the design of other dryers. The article deals with the method of vacuum-atmospheric drying of food products that are sensitive to high temperatures. The vacuum-atmospheric method includes vacuum drying of the material to intermediate humidity and atmospheric drying to the final moisture content. The principle of vacuum-atmospheric drying is based on the use of a refrigerating machine in the design of the dryer as a low-potential source for the capture and condensation of evaporating moisture vapor, as well as a high-potential resource-a heat pump. Three designs of vacuum-atmospheric dryers are developed. The dryers consist of three main elements, as a unit of vacuum drying, a unit of the heat pump and a unit of atmospheric final drying of thermolabile materials. The dryers consist of three main elements, such as a vacuum drying unit, a heat pump unit and an atmospheric drying unit for thermolabile materials. Dryers are equipped with measuring devices for measuring temperature, pressure and speed. Optimum modes of operation of vacuum-atmospheric drying of food products are developed. With a good quality of dried products, the vacuum-atmospheric drying method of food products contributes to a reduction in energy consumption compared to vacuum drying by 13-46%.

Keywords: drying, vacuum-atmospheric, dryer, food product, thermolabile, installation, Assembly, refrigerating machine, drying, heat pump.

Introduction. The issue in developing of new and innovative drying techniques is still actual one [1, 2]. Main reasons to accelerate attempts for development of advanced drying techniques are: making the process cost effective, reducing the energy consumption, intensifying the drying rates, improving the quality of dried food products, increasing safety in operation and making the drying process easy to control [3]. To some of advanced drying techniques may be related superheated steam drying, heat pump drying, multi-stage drying, spray freeze drying, inert atmosphere drying, microwave assisted drying, contact sorption drying and impinging stream drying [3].

Heat pump drying seems more efficient because of simplicity of design of dryer and high level of latent heat recovery. Furthermore, it has such advantages as improved product quality; possibility of variable temperatures and humidity for drying; excellent control of drying conditions; possibility of recovery of volatiles; less shrinkage degree [3-5]. At heat pump drying specific moisture extraction rate (SMER) is three times higher than hot air dryer [6], therefore it is expedient to incorporate heat pump in designs of other dryers.

Food products having strongly limited diapasons of heat and humid modes of drying, i.e. thermolabile materials, apply as a rule, methods of vacuum and vacuum-sublimation drying which are the best ways to dehydrate most of the food products [7]; however, they are associated with increased cost and

cannot be applied for wide range of foods. As noted Woodroof J. G. and Luh, increased costs associated with the manufacture, installation and maintenance of equipment [8].

At the same time, drying by a heat pump takes place at low temperatures (10–60°C). The heat pump dryer is a further extension of the conventional convection dryer with an inbuilt refrigeration system [9].

During vacuum drying the product is exposed to vacuum and heat [9] treatment. Vacuum allows moisture to evaporate at lower temperatures than atmospheric drying [10]. In addition, the low level of oxygen in the atmosphere reduces the intensity of oxidative reactions during drying. As a result, the color, texture and odor of the product dried by vacuum drying method are much better than the product dried by atmospheric drying method. In some cases, the quality of the product is comparable to the quality of the product after the vacuum sublimation drying. The pressure interval during vacuum drying is within 101-0.6 kPa, at which heat transfer is carried out mainly by conductive method [11].

Baker [12] offered a “structural approach” for selection of dryer which is useful to take in mind at construction of their designs. It includes the following steps:

– list all key process specifications;
– carry out preliminary selection;
– carry out bench scale tests including quality tests;
– make economic evaluation of alternatives;
– conduct pilot-scale trials;
– select most appropriate dryer types.

Methods. The method of vacuum-atmospheric drying of thermolabile material including vacuum drying till intermediate humidity and atmospheric drying till final one provides both good food quality and significant decreasing of energy consumption [13]. The principle of vacuum-atmospheric drying is based on applying of refrigerating machine in a construction of dryer not only as low-potential source of heat for trapping and condensation of evaporated moisture but also as high-potential one – heat pump.

Thus, final drying is carried out by air heated with heat of condensation of refrigerant agent that allows decrease energy consumption for atmospheric drying and duration of vacuum drying.

Relying on the "structural approach" proposed by Baker [12], the development of schemes for experimental installations was made taking into account the following requirements:

– an apparatus must implement developed method of vacuum-atmospheric drying of thermolabile materials like dairy products, topinambour tubers etc.;
– an apparatus must provide supporting combination of vacuum and atmospheric drying of thermolabile material;
– designs of an apparatus must provide supporting of chosen drying modes;
– meanings of pressure and temperature of medium at vacuum drying must be easily achieved at industrial conditions;
– temperature and speed of drying agent at atmospheric drying must have parameters which correspond to optimal working modes of heat pump which in a scheme of dryer.

In order to determine the economical drying mode, the energy costs for the removal of 1 kg of moisture were calculated.

Power consumption was calculated taking into account the energy-consuming sources involved in the entire drying process: electric heaters E_h, vacuum pump E_v, refrigeration compressor E_c and blower of air condenser E_b:

$$E = E_h + E_v + E_c + E_b . \quad (1)$$

Analyzing this formula, it can be concluded that in vacuum drying, the energy costs for heating electric heaters E_h, the work of the vacuum pump E_v and the refrigerating compressor E_c were calculated, and at atmospheric drying the energy was consumed only by the blower E_b .

Results.

1. Schemes of vacuum-atmospheric dryer. The elaborated scheme of experimental dryer includes units of vacuum drying, heat pump and final atmospheric drying of thermolabile material.

Assignment of the vacuum drying unit is providing process of drying of foods into air-free space from initial humidity of material till intermediate one. The heat pump unit is intended to supply an atmospheric drying device by high-potential heat and provide a freeze-out device by low-potential heat.

The unit of final atmospheric drying is assigned for implementation of dehydration of foods at atmospheric pressure from intermediate humidity up to final one regulated by technical specifications for a final product. According to the chosen scheme, three versions of experimental dryer were developed which are shown on figures 1–3.

In all dryers the unit of vacuum drying includes vacuum chamber, vacuum pump and freeze-out device which turn up an evaporator of refrigerant machine. Vacuum chamber is made in view cylinder metal capacity by volume 6 dm^3 with hermetically closed lid. Shelves with capacities for product are installed into vacuum chamber. Necessary level of vacuum is created by vacuum pump VN-461, and regulated by vacuum valve.

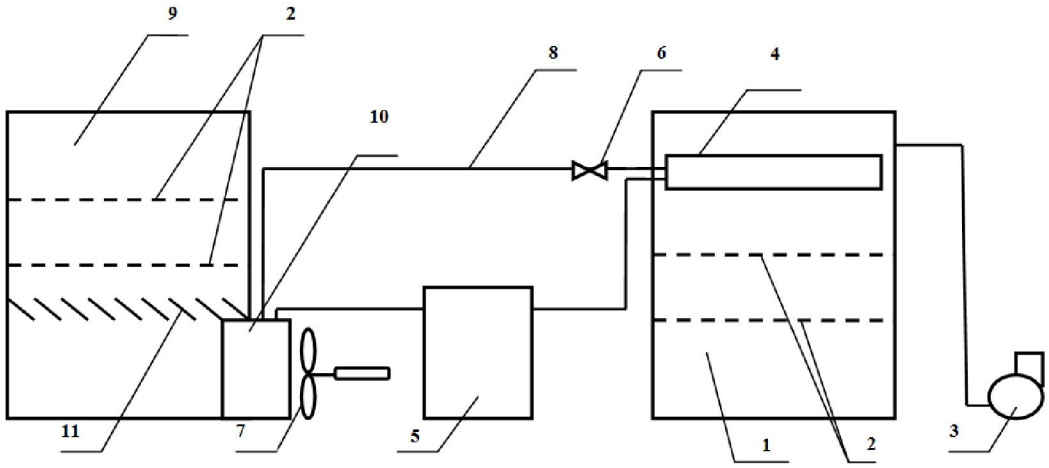

Figure 1 – Scheme of vacuum-atmospheric dryer with build-in evaporator:
1 – vacuum chamber; 2 – shelves; 3 – vacuum pump; 4 – evaporator; 5 – compressor; 6 – flow-regulating valve;
7 – axial blower; 8 – pipeline; 9 – device for final heat drying; 10 – condenser; 11 – blinds

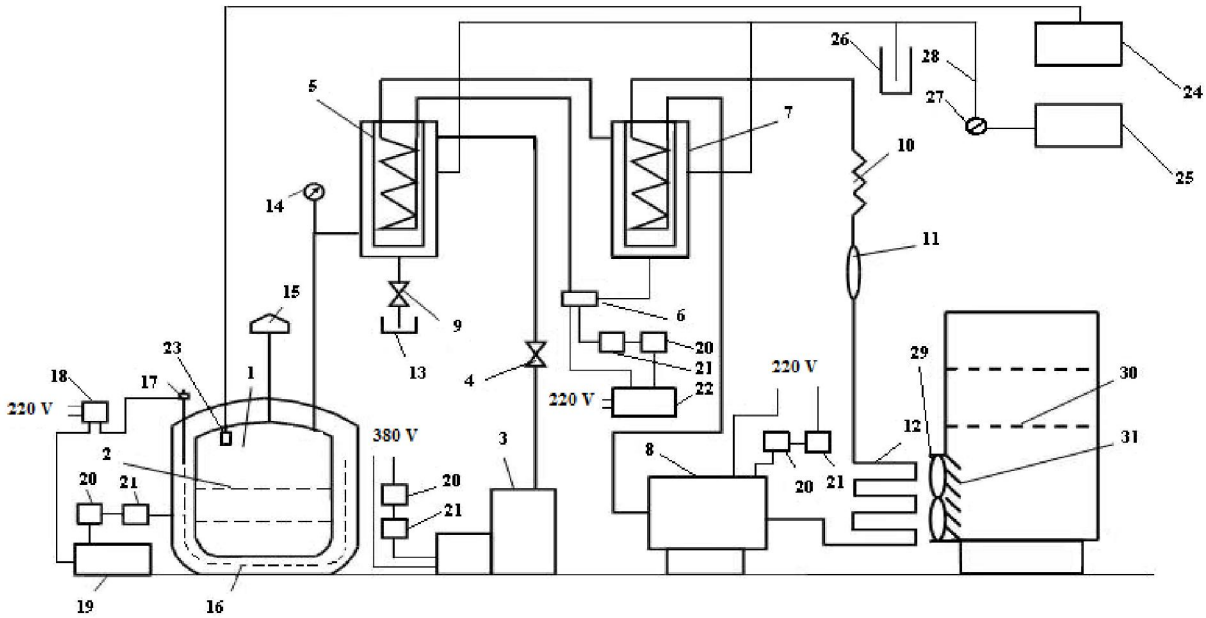

Figure 2 – Scheme of experimental vacuum-atmospheric dryer with two heat exchangers:
1 – vacuum chamber; 2, 30 – shelves; 3 – vacuum pump; 4 – regulating valve; 5 – refrigeration heat exchanger;
6 – liquid pump; 7 – evaporator of refrigeration machine; 8 – compressor of refrigeration machine; 9 – valve;
10 – capillary tube; 11 – filter-drier; 12 – condenser of refrigeration machine; 13 – condensate collector;
14 – indicating vacuum gauge; 15 – ionizing-thermocouple vacuum gage; 16 – electrical spirals; 17 – contact thermometer;
18 – regulating trigger; 19 – laboratory transformer; 20 – amperemeter; 21 – voltmeter; 22 – reducing transformer;
23 – resistance thermometer; 24 – multiple purpose meter; 25 – millivoltmeter; 26 – insulated can;
27 – positional cut-out switch; 28 – copper-constantan thermocouples; 29 – axial blower; 31 – blinds

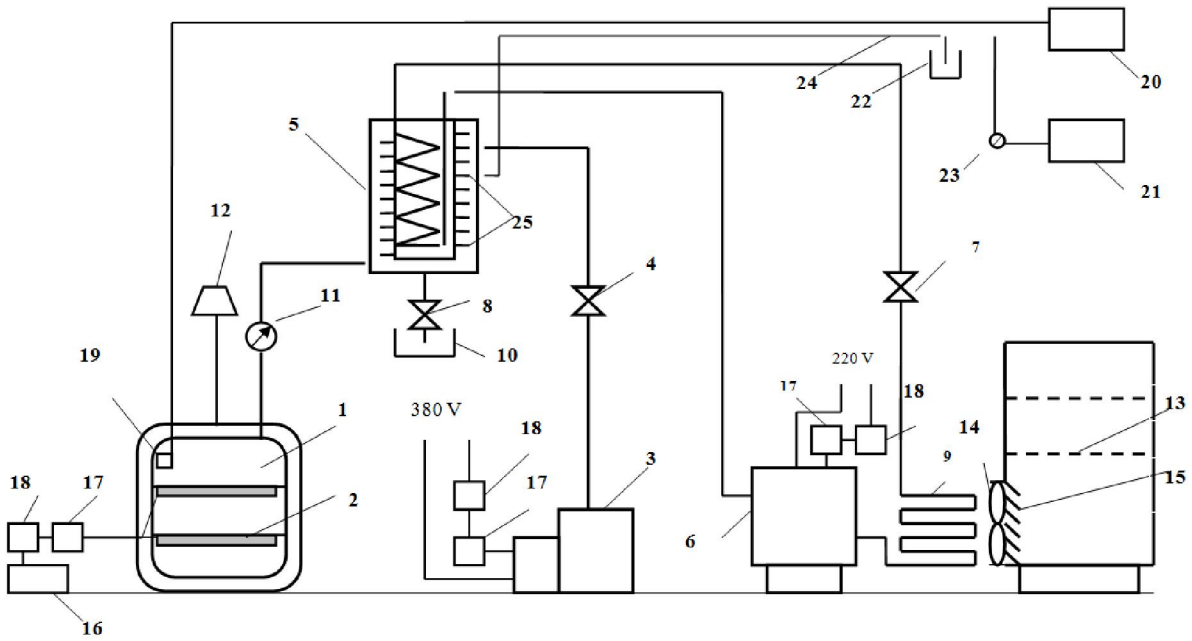

Figure 3 – Scheme of experimental vacuum-atmospheric dryer with one heat-exchanger:
1 – vacuum chamber; 2, 13 – shelves; 3 – vacuum pump; 4 – vacuum valve; 5 – evaporator; 6 – reciprocating compressor; 7 – flow-regulating valve; 8 – valve; 9 – air condenser; 10 – condensate collector; 11 – indicating vacuum gauge; 12 – ionizing-thermocouple vacuum gage; 14 – axial blower; 15 – louver nozzles; 16 – laboratory transformer; 17 – amperemeter; 18 – voltmeter; 19 – resistance thermometer; 20 – multiple purpose meter; 21 – millivoltmeter; 22 – insulated can; 23 – positional cut-out switch; 24 – copper-constantan thermocouples; 25 – baffles

The heat pump unit represents one-stage Freon refrigerating machine integrated into scheme of the apparatus. It allows significantly decrease duration of dehydration and energy consumption due to parallel implementation of processes of vacuum and atmospheric drying. Furthermore, incorporation of refrigeration machine into scheme of dryer permits to lower loading on vacuum pump because of trapping and condensation of water steam evaporated from surface of material into freeze-out device. Figure 1 shows a scheme of dryer where freeze-out device or evaporator of refrigeration machine is located in top part of vacuum chamber.

The unit of atmospheric drying includes device for final heat drying of thermolabile material, condenser of refrigeration machine and axial blower. The device for final atmospheric heat drying is made in view rectangular-sectioned carcass by working volume approximately 6 dm^3. Capacities with drying material are placed on mesh shelves. Condenser of refrigeration machine is assigned for heating of drying agent, i.e. air. Drying agent is delivered by axial blower into device for final heat drying. Uniformity of blowing of drying material is provided by regulation of position of blinds installed in low part of the device.

Modes of vacuum-atmospheric drying of thermolabile material were determined on dryer shown in figure 1. However, as experience shows, evaporator of refrigeration machine is essentially to locate separately for better exploitation of working volume of vacuum chamber. For the purposes design of dryer is altered to views shown in figures 2 and 3.

In the dryer (figure 3) steams of refrigerant agent are tightened in one-stage reciprocating compressor, cooled and condensed into air condenser. Liquid refrigerant agent is restricted and evaporated partially at passing through a flow-regulating valve and boils in an evaporator of refrigeration machine. The evaporator is designed in view air-to-air heat exchanger. Inner tube of the heat exchanger is filled by heat transfer medium. There is a coil pipe with circulated refrigerant agent into inner tube of the heat exchanger. A mixture of water steam and air pumped out with vacuum pump is moved by counter-current flow into annular space. A heat transfer medium takes away heat of evaporated water steam. In turn, refrigerant agent accepts heat of evaporated water steam and boils; it proves condensation and freezing of water steam. Baffles are installed on inner surface of external tube for long contact of water steam with

cooled surface of inner tube. The heat exchanger is covered by foamed polyurethane for protecting from heat infiltration. Frozen out moisture is defrosted and removed periodically from the evaporator through a valve into a capacity.

In the vacuum chamber, in order to accurately supply heat to the dried material, under each shelf mounted spiral electric heaters. Power of electrical heaters is regulated by laboratory transformer. The distance between shelves is regulated by means of dismountable pillars with different heights.

Inside the device for final drying materials mesh shelves are installed. Warm air heated by the condenser of the refrigerating machine is pumped into the lower part of the device with the help of an axial blower. Regulation of the flow and speed of the pumped air is made with the help of louver nozzles.

The dryer is equipped by gauges for registration pressure, temperature and rate of air in the main elements of the unit, as well as voltage and current consumed by the electrical devices of the unit.

The pressure in the vacuum drying chamber is measured by a rotary vacuum gauge VTP-160 or ionization-thermocouple vacuum gauge. Measurement of current and voltage is carried out by turnout amperes and voltmeters. The temperature of the medium in the chamber is measured by a wiry resistance thermometer which sense element is platinum wire with a diameter of 5 micron. Multiple purpose meter serves as secondary gauge for determination temperature into vacuum chamber. The temperature of condensation and freezing of moisture and temperature of boiling of refrigerant agent into freeze-out device are measured by the copper-constantan thermocouples layered in height of the heat exchanger. The thermostatic ends of thermocouples are immersed in melting ice in a glass thermos. All thermocouples through positional cut-out switch are plug in to digital millivoltmeter. The temperature of material during drying is determined with thermocouples of the millivoltmeter.

The dryer shown in figure 2 allows more correctly regulate freezing-out temperature of evaporated moisture due to integrated into scheme a refrigeration heat exchanger. Therefore, firstly optimal working modes of refrigeration machine were determined on this dryer. Then the dryer was transformed to view shown in figure 3. A difference of this dryer from previous one is elimination of heat leakage because of incomplete recuperation of heat in refrigeration heat exchanger. It allows boosting working efficiency of refrigeration machine, and correspondingly, heat pump.

2. Modes of vacuum-atmospheric drying. The studies were conducted to test the drying modes of vacuum-atmospheric drier with a single heat exchanger. Taking in mind preservation of properties of thermolabile material the following working modes of vacuum-atmospheric dryer are chosen:

– at vacuum drying an interval of pressure (2÷10)Kpa, interval of temperature (35÷60) ^{0}C;

– at atmospheric drying interval of temperature (36÷40) ^{0}C; interval of air rate a (0,25÷0,4) m/s.

In order to determine the energy efficiency of the process, energy costs were calculated for the process of vacuum-atmospheric drying of tubers of topinambour, camel and mare's milk.

Figure 4 shows the dependence of power consumption on the drying mode during vacuum and vacuum-atmospheric drying of crushed topinambour tubers in the form of cubes with a layer height of 20 mm. In these experiments, the material was dried from the initial humidity of 77 to the final one 9%. Vacuum drying was carried out at the pressure of the medium 4, 6 and 8 kPa, and the heating temperatures of 35, 45 and 55 ^{0}C. Atmospheric drying was carried out at a temperature of 40 ^{0}C, air speed of 0.40 m/s. Material in a vacuum chamber was dried to critical moisture content, and then placed in a device for atmospheric final drying. The critical moisture content determined experimentally was in the range of 30-40%. It can be seen from figure 4 that at a heating temperature of 35 ° C with an increase in the degree of rarefaction of the medium from 8 to 4 kPa, with a vacuum and vacuum-atmospheric drying, the specific energy consumption decreases by (10-11)%, and at a temperature of 45 ^{0}C only by (2, 5-3)%. At a temperature of 55 ^{0}C in a given pressure range, an increase in the level of consumed electricity by (4.7-8.6)% is observed.

The lowest power consumption is observed at an ambient temperature of 45 ^{0}C. As can be seen from figure 4, at a medium pressure of 4 kPa and heating temperatures of 35 and 45 ^{0}C, the electricity consumption for the removal of 1 kg of moisture from the material is almost the same and has a minimum value. At a heating temperature of 45 ^{0}C, the change in the level of vacuum within (4-8) kPa has almost no effect on the amount of electricity consumption. Based on the calculated data and analysis of the curves shown in figure 4, in order to maximize energy consumption, it is most advisable to carry out the vacuum-atmospheric drying process at a medium pressure of 4 kPa and a heating temperature of 45 ^{0}C at vacuum

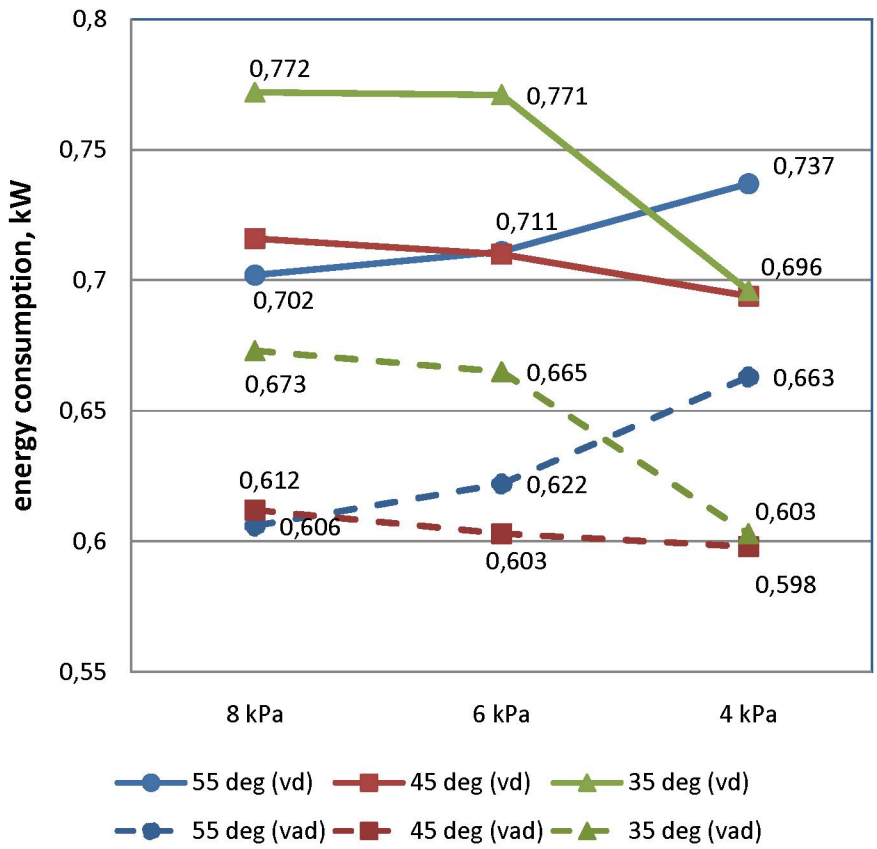

Figure 4 – Dependences of the electric power consumption on the drying mode at vacuum and vacuum-atmospheric drying (the solid line – vacuum drying; the dashed line – vacuum-atmospheric drying)

drying, a temperature of 40 ^{0}C and an air speed of 0.40 m/s at atmospheric drying. The increased power consumption at 35 ^{0}C is most likely due to the long duration of the process.

In general, the use of vacuum-atmospheric drying for crushed topinambour tubers in comparison with vacuum allows reducing the energy consumption by approximately 13-14%.

Energy costs for vacuum and vacuum-atmospheric drying of camel and mare's milk are calculated under the following regime parameters:

a) mode 1 - vacuum drying at a medium pressure of 10 kPa and a medium heating temperature of 40 ^{0}C with atmospheric drying at an air temperature of 36 ^{0}C;

b) mode 2 - vacuum drying at a medium pressure of 8kPa and a medium heating temperature of 45 ^{0}C with atmospheric drying at an air temperature of 38 ^{0}C;

C) mode 3 - vacuum drying at a medium pressure of 6kPa and a medium heating temperature of 40 ^{0}C with atmospheric drying at an air temperature of 40 ^{0}C.

During vacuum-atmospheric drying, the material was dehydrated in the vacuum chamber for the first half of the whole process, and the second half – in the device for atmospheric drying.

Table shows the data on energy consumption calculated for formula (1) for removing 1 kg of moisture during vacuum and vacuum-atmospheric drying of camel and mare's milk.

As can be seen from the table 1, the largest energy costs are observed in vacuum drying and lies within the limits of (1.966÷2.738) kW for camel and (1.831÷2.580) kW for mare's milk. Due to the use of the waste heat of refrigerant condensation during atmospheric dehydration and reduction of the duration of the vacuum drying under vacuum-atmospheric drying process, a significant reduction in energy costs is observed. For vacuum-atmospheric drying, the reduction in energy consumption compared to vacuum drying is (44÷46)%, which is (1,102÷1,489) kW for camel and (1,033÷1,408) kW for mare's milk. This is due to the fact that under vacuum-atmospheric drying, vacuum drying takes place only up to the middle of the process, and at atmospheric drying, electric energy is consumed only by an axial blower which pumps the air heated by the condenser.

Data on energy consumption for the removal of 1 kg of moisture during vacuum and vacuum-atmospheric drying of camel and mare's milk

The mode	The amount of energy spent on removing 1 kg of moisture, kW			
	vacuum drying		vacuum-atmospheric drying	
	camel milk	mare's milk	camel milk	mare's milk
mode 1	2,365	2,352	1,310	1,304
mode 2	1,966	1,831	1,102	1,033
mode 3	2,738	2,580	1,489	1,408

From the point of view of the drying mode, it can be concluded that the lowest energy consumption is observed at mode 3, regardless of the drying method. For vacuum drying, the medium pressure is 6 kPa and the temperature of the heaters is 40 ^{0}C, and for vacuum-atmospheric – with the same vacuum drying mode and atmospheric drying at an air temperature of 40 ^{0}C.

Thus, as shown by the results of experimental studies, the proposed method of vacuum-atmospheric drying of camel and mare's milk allows to achieve an increase in the efficiency of drying of the material by (44÷46)% due to the parallel implementation of vacuum and atmospheric drying processes.

Discussion. The idea of combining vacuum drying with other methods is also proposed by other scientists. Thus, hybrid drying is proposed, which includes the combination of vacuum drying with traditional and novel methods of drying, such as drum, microwave, infrared, ohmic drying [11].

Interestingly, when using pulsating and constant microwave treatment during vacuum drying of tea leaves, the energy consumption is higher in the first case [14]. This is due to the fact that constant microwave processing provides a continuous supply of energy, so the amount of absorbed energy by the dried product becomes larger, which leads to an increased rate of evaporation of moisture.

The essence of combining vacuum drying with atmospheric one is to include a heat pump in the vacuum drying unit, which supplies heat to the process of atmospheric drying of the material and cold to dehumidification process (freezing of moisture) during vacuum drying.

Experimental investigation of vacuum-atmospheric drying of solid-moist and liquid-viscous material by the example of topinambour tubers, camel and mare's milk were conducted on the dryer. Optimal meanings of intermediate humidity to which the material is dehydrated in vacuum chamber are defined: for solid-moist material it is critical humidity characterizing finishing period of constant rate of drying; for liquid-viscous material is intermediate humidity which is achieved at half drying time.

A good preservation of the biochemical composition of dried products and a reduction in the energy consumption of vacuum-atmospheric drying as compared with the vacuum one by 13-46% are noted, depending on the type of the material to be dried (solid or liquid). The results of studies of other scientists confirm the lower energy costs when drying with a heat pump, which reach 60-80% [15]. At the same time, the sensory characteristics of the product are perfectly preserved [16, 17, 18, 19]. Halawder at al found that the drying heat pump retains not only the color, but also the rehydration ability of the dried products [20]. Designs of the dryers are protected by patents of Republic of Kazakhstan [21-23].

Thus, the developed designs of dryers implementing methods of vacuum-atmospheric drying meet the requirements for advanced drying technologies, which makes the process cost-effective and reduces energy consumption.

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ТАМАҚ ӨНІМДЕРІН ВАКУУМДЫҚ ЖӘНЕ АТМОСФЕРАЛЫҚ КЕПТІРУ НЕГІЗІНДЕГІ КЕПТІРГІШТЕРДІҢ КОНСТРУКЦИЯЛАРЫ

Аннотация. Тамақ өнімдерін құрғатудың озық технологиялары арасында жылу сорғысымен кептіру кептіргіштің қарапайым конструкциясымен және жылуды тұйық рекуперациялаудың жоғары деңгейімен ерекшеленеді. Ол кептірілген өнімнің сапасына және кептіру режимдерін реттеуге қатысты бірқатар артықшылықтарға ие, сондықтан жылу сорғысын басқа кептіргіштердің конструкциясына қосу орынды. Мақалада жоғары температураға сезімтал тамақ өнімдерін вакуумдық-атмосфералық кептіру әдісі қарастырылады. Вакуумдық-атмосфералық әдіс аралық ылғалдылыққа дейін материалды вакуумдық кептіруді және соңғы ылғалдылыққа дейін атмосфералық кептіруді қамтиды. Вакуумдық-атмосфералық кептіру принципінің негізіне буланатын ылғал буындарын ұстау және конденсациялау үшін төмен әлеуетті көз ретінде, сондай-ақ жоғары әлеуетті ресурс-жылу сорғысы ретінде тоңазытқыш машинаны қолдану жатады. Вакуумды-атмосфералық кептіргіштердің үш құрылымы әзірленді. Кептіргіштер вакуумдық кептіру торабы, жылу сорғысының торабы және термолабильді материалдардың атмосфералық кептіру торабы сияқты үш негізгі элементтен тұрады. Кептіргіштер температураны, қысымды және жылдамдықты өлшейтін өлшеу құралдарымен жабдықталған. Тағам өнімдерін вакуумдық-атмосфералық кептіру жұмысының оңтайлы режимдері әзір-

ленді. Кептірілген өнімнің сапасы жақсы болған жағдайда тамақ өнімдерін вакуумдық-атмосфералық кептіру әдісі вакуумдық кептірумен салыстырғанда энергия шығынын 13-46%-ға төмендетуге ықпал етеді.

Түйін сөздер: кептіру, вакуумды-атмосфералық, кептіргіш, тамақ өнімі, термолабильді, қондырғы, торап, тоңазытқыш машина, қайта кептіру, жылулық сорап.

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КОНСТРУКЦИИ СУШИЛОК НА ОСНОВЕ СОВМЕЩЕНИЯ ВАКУУМНОЙ И АТМОСФЕРНОЙ СУШКИ ПИЩЕВЫХ ПРОДУКТОВ

Аннотация. Среди передовых технологий обезвоживания пищевых продуктов, сушка тепловым насосом отличается простотой конструкции сушилки и высоким уровнем скрытой рекуперации тепла. Она обладает рядом преимуществ в отношении качества сушеной продукции и регулирования режимов сушки, поэтому целесообразно включение теплового насоса в конструкции других сушилок. В статье рассматривается метода вакуумно-атмосферной сушки пищевых продуктов, которые чувствительны к высоким температурам. Метод вакуумно-атмосферной включает вакуумную сушку материала до промежуточной влажности и атмосферную досушку до конечного влагосодержания. В основу принципа вакуумно-атмосферной сушки положено применение холодильной машины в конструкции сушилки как низкопотенциального источника для улавливания и конденсации испаряющихся паров влаги, а также как высокопотенциального ресурса – теплового насоса. Разработаны три конструкции вакуумно-атмосферных сушилок. Сушилки состоят из таких трех основных элементов, как узел вакуумной сушки, узел теплового насоса и узел атмосферной досушки термолабильных материалов. Сушилки оборудованы измерительными приборами для измерения температуры, давления и скорости. Разработаны оптимальные режимы работы вакуумно-атмосферной сушки пищевых продуктов. При хорошем качестве сушеной продукции метод вакуумно-атмосферной сушки пищевых продуктов способствует снижению энергозатрат по сравнению с вакуумной сушкой на 13-46%.

Ключевые слова: сушка, вакуумно-атмосферный, сушилка, пищевой продукт, термолабильный, установка, узел, холодильная машина, досушка, тепловой насос.

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