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DETERMINATION OF HEAT TRANSFER MECHANISMS DURING VACUUM DRYING OF SOLID-MOIST AND LIQUID-VISCOUS MATERIALS

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Most drying methods combine convective, conductive and radiation heat transfer processes. The share of each type of heat transfer may vary depending on the type and mode of drying, type of product, etc. In this study, the problem of determining the heat transfer mechanism of vacuum drying of solid-moist and liquid-viscous materials is solved. The objects of the study are Jerusalem artichoke tubers, camel and mare milk. The numerical values of the heat transfer components are found experimentally and their shares in the total heat flux are determined. During vacuum drying of Jerusalem artichoke at a medium pressure of 4 kPa and a temperature of 55 °C (with a layer height of 0.01 and 0.02 m), the convective component predominates (58.55 and 67.65 %). The share of thermal conduction (18.96 and 29.39 %) and radiation (13.39 and 12.05 %) is much lower. The mechanism of thermal conduction begins to prevail with an increase in the height of the material layer (0.03 and 0.04 m). The convective component is also dominant for vacuum drying of milk: at medium pressures of 6÷10 kPa and a temperature of 40 °C, its value for mare milk reaches 78.21 %, for camel milk – 73.33 %. The second most important is the share of radiation (19.45 and 22.58 %). Conductive heat transfer has the minimum indicators (5.66 and 6.17 %). The large values of the share of thermal conduction during drying of Jerusalem artichoke compared to milk are explained by the fact that heat transfer occurs inside the tubers due to conduction, and inside milk – due to convection. Insignificant shares of radiation are explained by low and medium vacuum values in the chamber. In the studied range, heat and mass transfer occurs due to molecular diffusion and convection. The results obtained can be used to formulate criterion heat transfer equations, in engineering calculations, and optimization of the vacuum dryer operation

Keywords: vacuum drying, heat transfer mechanism, heat transfer shares, Jerusalem artichoke tubers, camel milk, mare milk

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1. Introduction

Studies of vacuum drying of food products confirm its effectiveness [1–3]. Unlike vacuum freeze drying, vacuum dehydration occurs without preliminary freezing of the material to be dried, at a significantly high pressure of the medium and positive temperatures. This provides significant energy efficiency with a good quality of the final product. As a rule, the vacuum level is in the medium and low range, which determines the features of the heat transfer mechanism during vacuum drying. In this region, the heat transfer mechanism is transient and changes with the deepening of the vacuum degree. Radiation and conductive heat transfers are dominant during freeze drying, convective and conductive heat transfers – in atmospheric drying, while in vacuum dehydration, the influence of all three heat transfer components must be taken into account. The shares of heat transfer during vacuum drying will vary depending on the vacuum degree of the medium. Knowledge of the heat transfer mechanism is necessary to justify the nature of the criterion equations used in engineering calculations of drying plants operating at medium and low vacuum.

Therefore, studies on determining heat transfer mechanisms and their quantitative ratio during vacuum drying of solid-moist and liquid-viscous materials are relevant.

2. Literature review and problem statement

Heat transfer in thermal processes can be carried out in three ways: convection, thermal conduction and radiation. In conduction, heat transfer occurs in solids due to lattice vibrations or particle collisions. Convection is based on the movement of liquids to transfer heat. Radiation doesn't need a medium to transfer heat, but uses electromagnetic waves emitted by an object for heat transfer [4]. Most drying methods are a combination of the above techniques, i.e. they consist of two or three methods of heat supply. At the same time, the share of each type of heat transfer can be different and vary depending on the type and mode of drying, the geometric parameters of the processed product, etc. Thus, during atmospheric drying, heat transfer occurs mainly due to convection and thermal conduction. In vacuum freeze drying, which takes place in a deep vacuum, heat is transferred mainly by thermal conduction and radiation. So, it is noted that the dominant mechanisms of heat transfer during freeze drying of pharmaceuticals are thermal conduction and radiation [5]. The share of the latter can vary depending on the type of surface material in the drying chamber. At low pressure, i.e. during freeze drying, heat is usually transferred to the product by thermal conduction, sometimes by radiation, and convection is rare, since there are very few liquid or gas molecules in a vacuum, and the heat transfer coefficient can be neglected [6]. If the product is located on heating shelves in a vacuum chamber, then the product will receive heat from the upper shelf due to radiation, from the lower shelf – by thermal conduction. In this case, conductive heat transfer prevails inside the product. Similarly, it is argued that during vacuum drying, heat is usually transferred to the product due to thermal conduction, sometimes by radiation [7].

Meanwhile, it was found that during freeze drying with a pressure of more than 100 mTorr, the convective component is comparable to the conductive one [8]. It is assumed that if vacuum drying proceeds at a residual pressure above 1–2 kPa, then the heat and moisture transfer of the dried product obeys the laws of heat and moisture transfer during convective drying [9].

It was also found that the share of radiation heat transfer during vacuum freeze drying of naphthalene lies within 30÷50 % of the total heat flux [10]. At the same time, no similar information was found in the scientific literature on vacuum drying, which occurs, as a rule, at low and medium degrees of vacuum, as well as at positive temperatures.

The mechanism of the heat transfer process changes depending on the degree of vacuum [11]. The degree of vacuum is proposed to be divided into 4 types.

To the first type, the authors attribute the transfer of heat and mass of matter in the pressure range from atmospheric to 40 mm Hg. Art. The first type is characterized by the fact that with a decrease in the total pressure of the vapor-air medium, the evaporation intensity grows slightly, having an almost linear relationship. In this case, the transfer of heat and mass of matter mainly occurs by molecular diffusion and convection. The steam-air mixture flow regime is laminar.

The second type is characterized by an intensive process of vacuum freeze evaporation, when a high drying rate leads to a change in the heat and mass transfer mechanism. During evaporation, moisture increases in volume and rushes into a vacuum medium. This hydrodynamic effect is significant if the vapor pressure of the substance is comparable in magnitude to the pressure in the freeze dryer. Heat transfer is completely determined by mass transfer, the hydrodynamics of which depends on the total pressure and the rate of change in the aggregate state of moisture. This type of heat and mass transfer occurs in the pressure range from 40 to 0.5 mm Hg.

The third type of transfer is characterized by a molecular-viscosity regime, in which the influence of a thin near-wall layer, which directly adjoins the freeze-dried surface, begins to affect.

The fourth type of heat and mass transfer is a free molecular transfer process, which is characterized by the absence of collisions between molecules. The mechanism of this type of heat and mass transfer is described by the kinetic molecular theory of gas.

The above studies are devoted to a greater extent to the study of heat transfer mechanisms during vacuum freeze drying of frozen materials, carried out under high vacuum. This method has been in the spectrum of interest of scientists for many years, since it contributes to the excellent preservation of the chemical composition and organoleptic characteristics of materials. At the same time, it becomes obvious that for a wide range of solid-moist and liquid-viscous materials, it is acceptable to use less energy-intensive vacuum drying. That is why it is necessary to focus research on the heat transfer mechanisms of dehydration of materials in low and medium vacuum conditions. At present, one can rely only on the above classification of vacuum degrees. Questions about the share of each type of heat transfer depending on the nature of the material under study, its geometric characteristics and heating temperature are still open. This problem is addressed in the present paper.

The technology of vacuum drying of food products and the installation for its implementation were described earlier [12, 13]. It includes preliminary preparation of raw materials, placing them in a vacuum chamber and drying to the required humidity. It should be noted that only the period of constant drying rate is considered, when the product temperature is constant and equal to the wet bulb temperature.

3. The aim and objectives of the study

The aim of the study is to determine the mechanisms of heat transfer and their quantitative ratio during vacuum drying of solid-moist and liquid-viscous materials. This will make it possible to justify the choice of the nature of the criterion equations used in engineering calculations for the design of drying plants.

To achieve the aim, the following objectives were formulated:

– to experimentally determine the numerical values of the heat transfer components of convection, thermal conduction and radiation and determine their shares in the total heat flux;

– to reveal patterns of changes in the numerical values of the heat transfer components.

4. Materials and methods

4. 1. Object and hypothesis of the study

The object of the study is vacuum drying of coarse-dispersed and liquid-viscous materials in an experimental facility.

The hypothesis of the study was as follows: it is assumed that convection will be the predominant type of heat transfer for vacuum drying of solid-moist and liquid-viscous materials in the studied pressure range.

The following simplifications were adopted: only the period of constant drying rate is considered, when the product temperature is constant and equal to the wet bulb temperature.

4. 2. Experimental vacuum dryer

The study of the role of each type of heat transfer during vacuum drying of solid-moist and liquid-viscous materials was carried out on an experimental dryer, the scheme of which is shown in Fig. 1.

The installation includes a vacuum chamber 1, a vacuum pump 6 and a moisture freezer 5, which is a refrigerator evaporator. The vacuum chamber is a metal cylindrical container with a hermetically sealed lid. In the vacuum chamber, there are shelves 3 for the material to be dried 2, under which electric heaters 4 are mounted. The required vacuum level in the chamber is created by the vacuum pump, and the required pressure level is controlled by a vacuum valve.

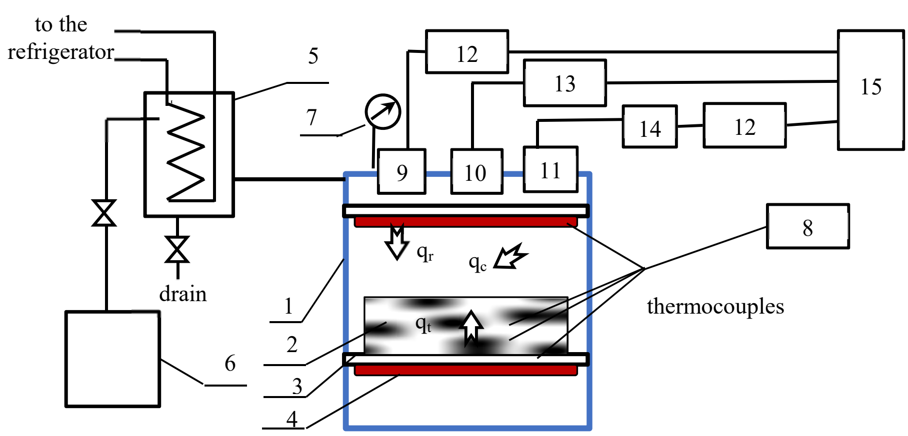


Fig. 1. Scheme of a vacuum dryer and methods of heat transfer: q_c – convection; q_r – radiation; q_t – thermal conduction; 1 – vacuum chamber housing; 2 – dried product; 3 – shelf; 4 – electric heaters; 5 – moisture freezer; 6 – vacuum pump; 7 – pointer vacuum gauge; 8 – digital DC voltmeter; 9 – pressure sensor for the vacuum medium; 10 – temperature sensor for the vacuum medium; 11 – surface sensor for the cylinder walls; 12 – strain gauge station; 13 – DC bridge; 14 – resistance box; 15 – multi-trace oscilloscope

Measurements of the temperature of the dried product were carried out by copper-constantan thermocouples with a diameter of 0.15 mm, located along the depth and width of the product, using a digital DC voltmeter 8 as a recording device.

Measurement of stationary pressures of the medium in the vacuum chamber was carried out with a vacuum gauge 7, and changes in the medium pressures were recorded by a strain gauge membrane pressure sensor 9 [14].

Measurement of the medium temperature changes in the vacuum chamber was carried out by a fast-response resistance thermometer 10 with a platinum wire 5 μm in diameter using a DC bridge 13 with an accuracy class of 0.1 [15].

Measurement of temperature fluctuations on the working surface of the chamber wall was carried out by a thin-film resistance thermometer 11 with a sensitive element made of a semiconductor alloy deposited on a polycor substrate. The thickness of the sensitive element is about 600 Å. The initial resistance of the sensitive element at a temperature of 293 K is about 3000 Ohm.

The multi-trace oscilloscope 15 was used as a recording device for changes in temperatures and pressures of the vacuum medium and walls of the vacuum chamber. In this case, the signal from the pressure sensor was preliminarily amplified by the strain gauge station 12. Interpretation of the oscillograms of changing temperatures and pressures of the vacuum medium and walls of the vacuum chamber was carried out according to the results of their calibration. The DC bridge 13 and the resistance box 14, also with an accuracy class of 0.1, were used to isolate constant mechanisms of signals from temperature and pressure sensors, as well as to interpret oscillograms directly on the oscilloscope scale.

In this scientific study, the degree of vacuum in the vacuum chamber varied within 4÷10 kPa, the heating temperature range was 35÷55 °C. This level of vacuum refers to the region of low and early medium vacuum [13], and the temperature range characterizes moderate heating.

Thus, heat transfer in the vacuum chamber took place by:

– thermal conduction (q_t) from the heated shelf on which the material is located,

– convection (q_c) from the air heated by electric heaters,

– radiation (q_r) from electric heaters and shelves.

In this case, heat transfer inside solid-moist materials occurred by conduction, in liquid materials – by convection.

4. 3. Materials used for vacuum drying

Jerusalem artichoke tubers and camel and mare milk were chosen as research materials.

The work examined Jerusalem artichoke tubers of spring harvest after overwintering in the soil. Camel and mare milk of spring milking was used.

Jerusalem artichoke (Helianthus tuberosus) is a perennial tuberous plant with medicinal properties. Tubers contain the soluble polysaccharide inulin, nitrogenous substances, vitamin C and a complex of B vitamins, organic and fatty acids. The minerals of Jerusalem artichoke are zinc, silicon, phosphorus, iron, potassium, magnesium and copper. Many studies confirm the feasibility of using Jerusalem artichoke as a functional product [16–18].

Camel and mare milk were studied as liquid-viscous materials.

Camel milk is richer in iron, zinc, copper, potassium, sodium, calcium, and vitamin C than cow's milk, making it closer to human milk. Camel milk also has valuable therapeutic properties as it contains a high concentration of antibacterial, antifungal, antiviral, and antiparasitic compounds. The latter help to fight such serious diseases as hepatitis, rotavirus diarrhea, tuberculosis and schistosomiasis [19]. Camel milk, as a natural and safe product, can be used as an alternative treatment for diabetes mellitus [20].

Mare milk has strong bactericidal properties. Compared to cow's milk, mare milk contains less fat, protein, and minerals, but 5–7 times more vitamin C [21]. The mineral composition of mare milk is represented by calcium, phosphorus, potassium, sodium, cobalt, copper, iodine, manganese, zinc, titanium, aluminum, silicon and iron. The high iodine number indicates a high content of unsaturated fatty acids (including polyunsaturated ones), due to which milk fat is quickly oxidized. Mare milk contains immunoglobulins, lactoferrin and lysozymes, which exhibit high biological activity and benefit the human body [22]. In addition, mare milk, which is not ruminant milk, is similar in nutritional composition to breast milk; modified mare milk is a safe substitute for cow's milk for infants with allergies [23].

Jerusalem artichoke tubers were cleaned, washed and cut into cubes. The prepared material (cubes of Jerusalem artichoke measuring 5×5×5 mm) was placed in mesh containers. The thickness of the material layer varied from 10 to 40 mm. The material was placed on the shelves as a dense layer.

The milk was filtered, cooled to 2÷8 °C and poured into a glass container. The height of the milk in the container was 10 mm.

4. 4. Modes and procedure of vacuum drying

Vacuum drying of Jerusalem artichoke tubers and milk was carried out in a non-frozen layer at moderate temperature heating.

Vacuum drying of Jerusalem artichoke tubers was carried out under the following conditions:

– medium pressure 4...8 kPa with a step of 2 kPa;

– heating temperature 35...55 °C with a step of 10 °C;

– the height of the layer of the dried material within 0.01...0.04 m with a step of 0.01 m.

Vacuum dehydration of camel and mare milk was carried out in the following modes:

– medium pressure 6...10 kPa with a step of 2 kPa;

– heating temperature 35...45 °C with a step of 5 °C;

– the height of the dried layer 0.01 m.

The choice of temperature and pressure ranges for vacuum drying was justified by the need to preserve the maximum biochemical composition of the studied drying materials at a sufficiently high intensity of the drying process.

Experimental studies were carried out in the following order:

1. 30 minutes before the start of the experiment, the compressor and electric heaters were turned on to prepare the dryer. The required refrigerant boiling point (–4 °C) was set by adjusting the throttle valve. The temperature of the heaters in the vacuum chamber was adjusted within 35÷55 °C by changing the current strength supplied to the electric heaters.

2. The mass of the material was determined by weighing on analytical scales with an accuracy of 0.001 g.

3. Containers with the material to be dried were placed on shelves in the vacuum chamber. The chamber lid was tightly closed.

4. After turning on the vacuum pump, the vacuum level of the medium in the chamber (4, 6, 8, 10 kPa) was set by a control valve. The start of the experiment was recorded after the required level of vacuum was reached.

5. The time interval between measurements of the weight of the dried material was 60 minutes. In this case, the amount of evaporated moisture was determined. First, the vacuum level in the chamber was reduced to 80 kPa using the vacuum valve; then the vacuum pump was turned off and the lid was opened.

6. The moisture content of the material was calculated by equation (1):

$$\omega = \frac{m_1 - m_2}{m_1} \cdot 100\,\%, \tag{1}$$

where ω is the moisture content of the material relative to the initial mass of the material, %; m_1 and m_2 are the initial and final masses of the material, kg.

The weighed material was again placed in the vacuum chamber and subjected to drying with an intermediate measurement of the material mass loss until the material reached critical humidity.

The critical humidity values were determined experimentally by plotting drying curves.

The initial moisture content of Jerusalem artichoke tubers was 77 %. The initial moisture content of camel milk was 86 %, mare milk – 90 %.

The mass of the dried material was measured on laboratory analytical scales.

7. The temperature of the dried material was constantly measured using copper-constantan thermocouples, as well as the temperature of the medium in the vacuum chamber using the resistance thermometer.

4. 5. Calculation of heat transfer components

The amount of heat spent on heating Q_h and moisture evaporation Q_{ev} from the material was determined by equation (2):

$$Q = Q_h + Q_{ev} = cm\Delta T + rm_w, \tag{2}$$

where c is the specific heat capacity of the product, J/kg K; m is the mass of the product, kg; m_w is the mass of water removed from the product, kg; ΔT is the difference between the final and initial temperatures of the product, K; r is the specific heat of vaporization, J/kg.

The amount of heat transferred by thermal conduction Q_t was calculated by the formula (3)

$$Q_t = -\lambda \Delta T_s \frac{\Delta\tau}{s}, \tag{3}$$

where λ is the effective thermal conductivity of the material at its temperature, W/m·K; s is the layer thickness, m; ΔT_s is the temperature difference between the heater and the product surface; Δτ is the duration of the period of constant drying rate, s.

The amount of heat transferred by radiation Q_r was determined by the formula (4)

$$Q_r = \varepsilon\sigma F\left(T_1^4 - T_2^4\right)\Delta\tau, \tag{4}$$

where σ is the Stefan-Boltzmann constant equal to 5.669×10^{-8} W/(m^{2}K^4); ε is the reduced coefficient of thermal radiation; T_1 is the temperature of the heaters; T_2 is the surface temperature of the product, F is the area through which heat passes.

The reduced thermal radiation coefficient ε was calculated as for the case of heat transfer between two plates, i.e. heaters and the product [24]:

$$\varepsilon = \left[\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1\right]^{-1}, \tag{5}$$

where ε_1 is the coefficient of thermal radiation of heaters; ε_2 is the coefficient of thermal radiation of the product.

The specific heat capacity *c* and thermal conductivity λ of the product were calculated at the wet bulb temperature using the equation taken from reference literature [25]. The value of the thermal radiation coefficient of metal heaters ε_1 is taken from [26]. ε_2 was determined experimentally by equation [27]:

$$\varepsilon_2 = 0.0347\sqrt{r_0}T, \quad (6)$$

where r_0 is the resistivity at 273 K, Ohm·cm; *T* is the product temperature, K.

The amount of heat transferred by convection Q_c was calculated from the heat balance equation as follows:

$$Q_c = Q - Q_t - Q_r. \quad (7)$$

From the obtained experimental data on the material and medium temperatures, using equations (1)–(7), the share of each type of heat transfer in relation to the total amount of heat consumed was calculated.

In accordance with the aim of the study, the numerical values of the heat transfer components – convection, radiation and thermal conduction were experimentally determined and their shares in the total heat flux were calculated. The results are presented in the diagrams shown in Fig. 2–4 for Jerusalem artichoke tubers and in Fig. 5, 6 for mare and camel milk.

5. Results of the study of heat transfer mechanisms during vacuum drying

5. 1. Experimental determination of the numerical values of the heat transfer components

Fig. 2–4 show the ratios of the heat transfer components depending on the pressure of the medium (4, 6 and 8 kPa) and the height of the layer (0.1; 0.2; 0.3 and 0.04 m) at a heating temperature of 35, 45 and 55 °C for Jerusalem artichoke tubers.

Fig. 5, 6 show the ratios of the heat transfer components depending on the pressure of the medium (6, 8 and 10 kPa) and the heating temperature (35, 40 and 45 °C) for camel and mare milk.

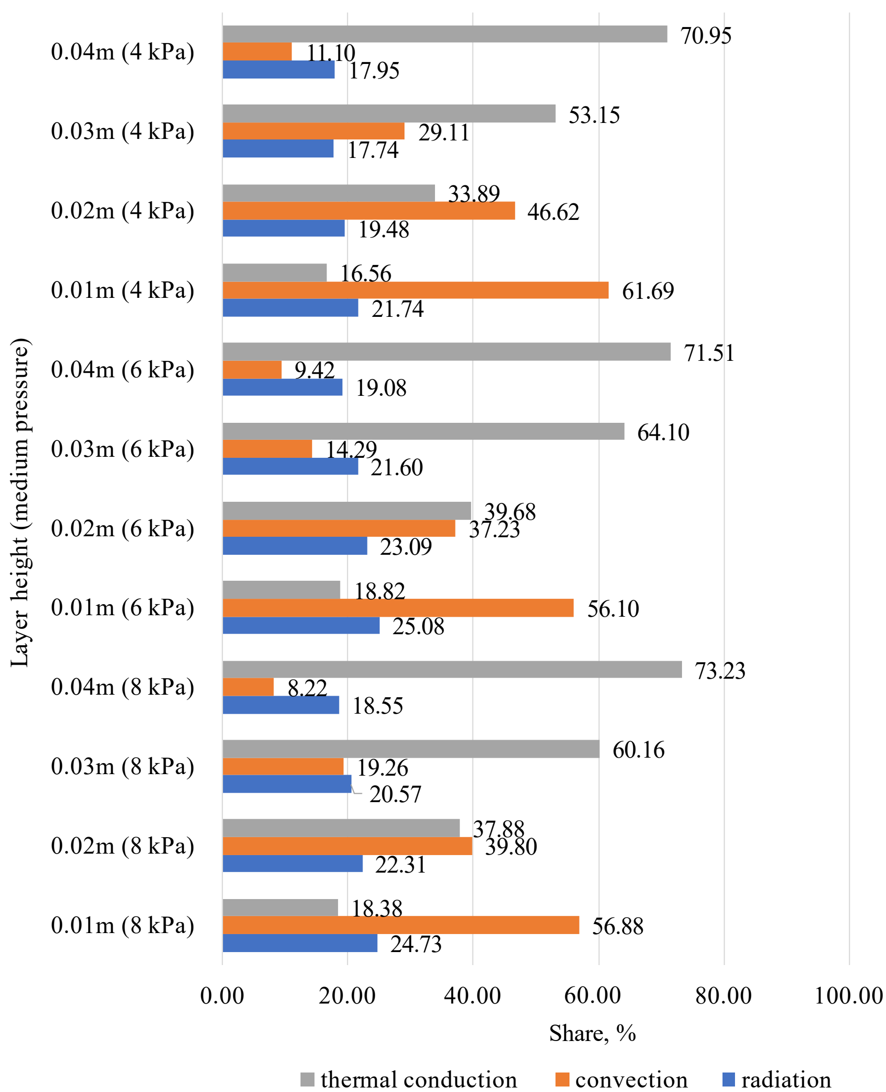


Fig. 2. The share of each type of heat transfer (%) during vacuum drying of Jerusalem artichoke tubers at a temperature of 35 °C

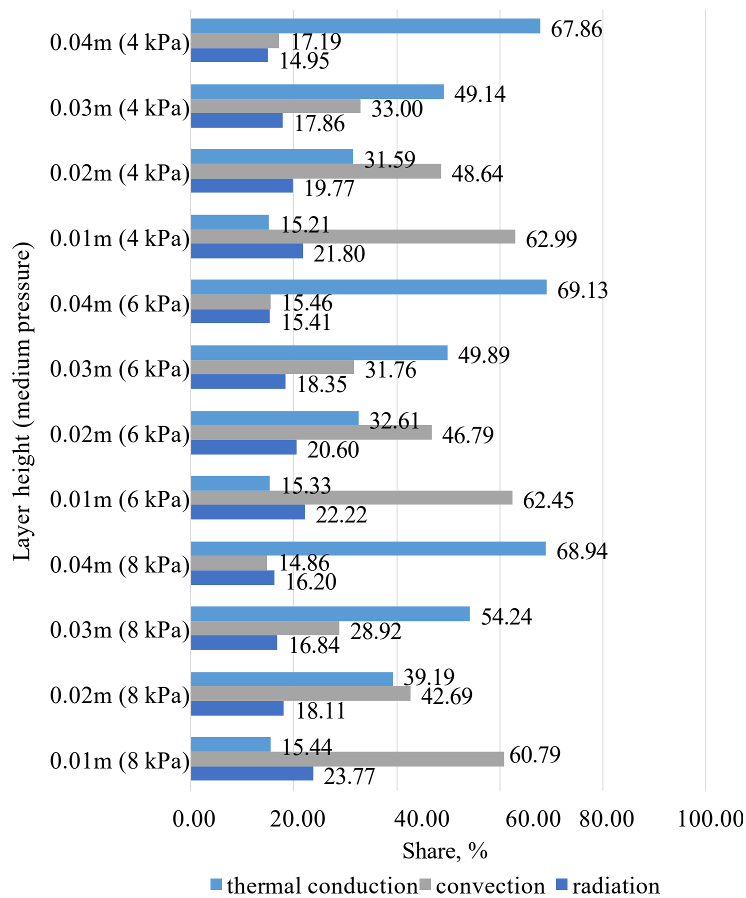


Fig. 3. The share of each type of heat transfer (%) during vacuum drying of Jerusalem artichoke tubers at a temperature of 45 °C

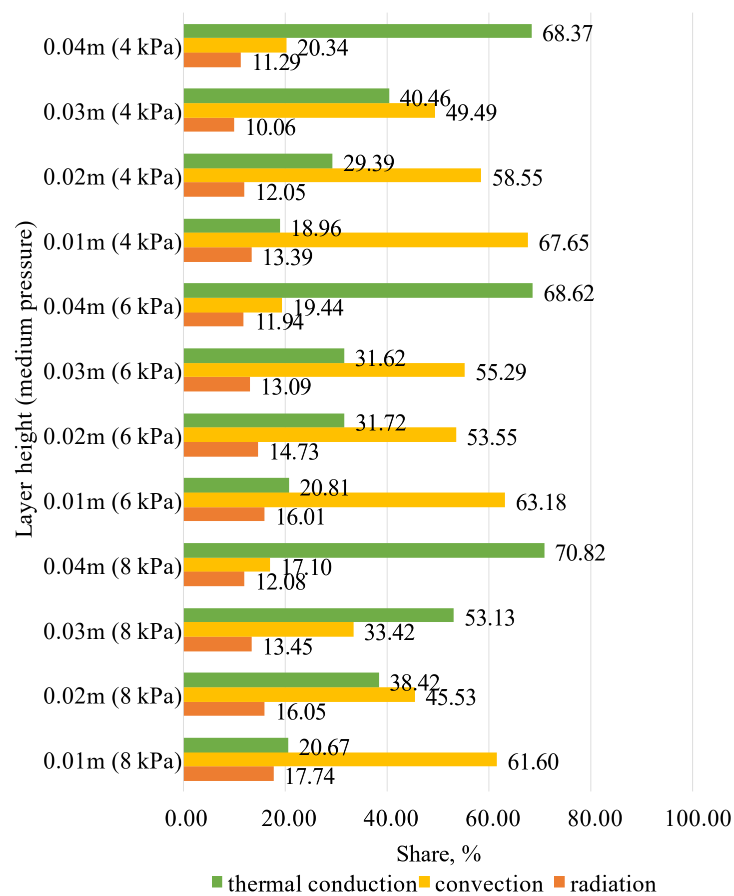
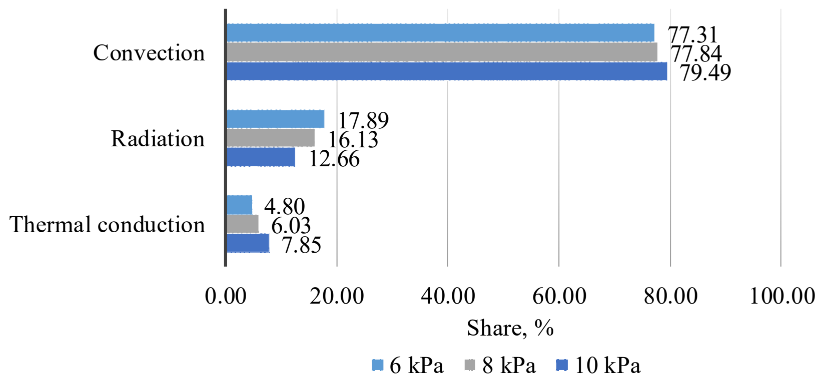
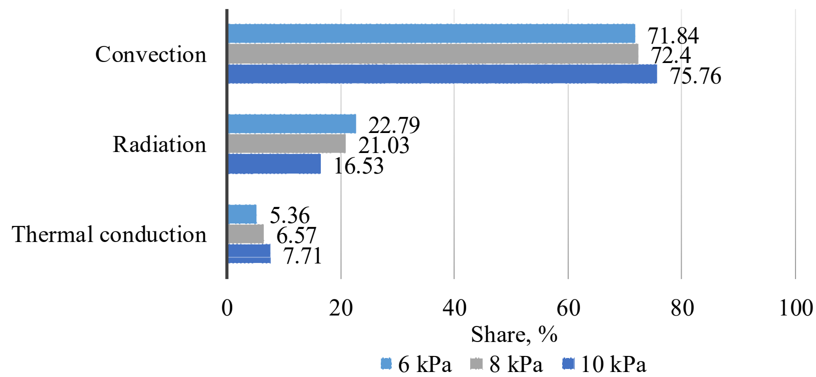


Fig. 4. The share of each type of heat transfer (%) during vacuum drying of Jerusalem artichoke tubers at a temperature of 55 °C

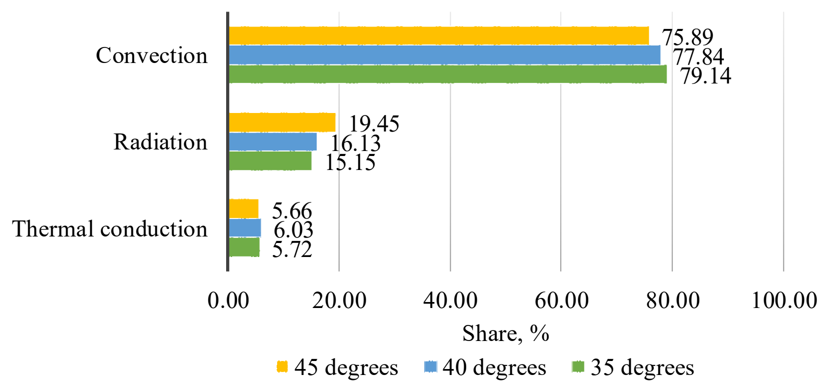


a

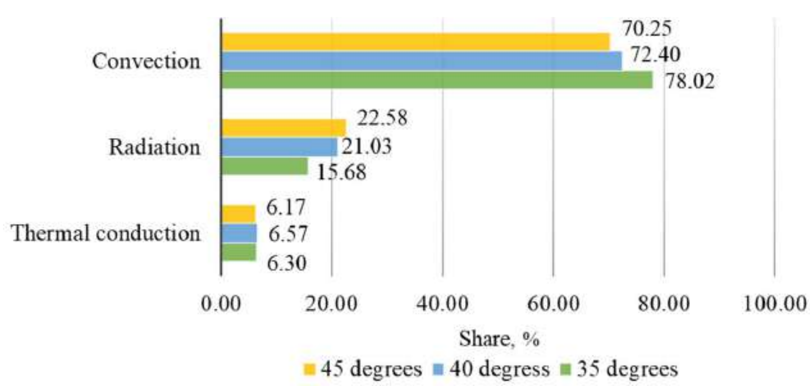


b

Fig. 5. Shares of each type of heat transfer during vacuum drying of mare and camel milk at a temperature of 40 °C, depending on the pressure of the vacuum medium: *a* – mare milk; *b* – camel milk



a



b

Fig. 6. Shares of each type of heat transfer during vacuum drying of mare and camel milk at a medium pressure of 8 kPa, depending on temperature: *a* – mare milk; *b* – camel milk

5. 2. Revealing the patterns of changes in the numerical values of the heat transfer components

The analysis of Fig. 2 shows minor changes in the share of radiation depending on the vacuum value and the height of the layer of Jerusalem artichoke tubers at a heating temperature of 35 °C. It varies within 17.74…25.08 %. In this case, the values of convective heat fluxes change much more. At a medium pressure of 8 kPa, with an increase in the layer height from 0.01 to 0.04 m, the value of the convective flow decreases from 56.9 to 8.22 %. At a medium pressure of 6 kPa, this indicator decreases from 56.10 to 9.42 %, at 4 kPa – from 61.69 to 11.10 %. It follows that the share of the convective flow practically doesn't change depending on the degree of vacuum in the range of 8…4 kPa, but falls significantly with increasing layer height. This is explained by the fact that with an increase in the layer height, the share of conductive heat transfer increases, i.e. thermal conduction, which is logical. So, with an increase in the layer height from 0.01 to 0.04 m, the share of heat supplied due to thermal conduction at a pressure of 8 kPa increases from 18.38 to 73.23 %, at 6 kPa – from 18.82 to 71.5 %, at 4 kPa – from 16.56 to 70.95 %, i.e. in direct ratio.

A similar nature of the ratio of heat transfer components is observed at a heating temperature of 45 °C (Fig. 3). The values of the radiation component also change slightly with a change in the vacuum degree, but they are lower than at a heating temperature of 35 °C, and are in the range of 14.95…22.22 %. The values of the convective component at a medium pressure of 8 kPa with an increase in the layer height from 0.01 to 0.04 m decrease from 60.79 to 14.86 %, at 6 kPa – from 62.45 to 15.46 %, at 4 kPa – from 62.99 to 17.19 %. These values are somewhat higher than the values of the convective components at a temperature of 35 °C. The share of the flows provided by thermal conduction at 8 kPa with an increase in the layer height from 0.01 to 0.04 m increases in direct proportion – from 13.44 to 68.94 %, at 6 kPa – from 15.33 to 69.13 %, at 4 kPa – from 15.21 to 67.86 %. These values are slightly lower than in the previous heating mode.

At a heating temperature of 55 °C, the share of radiation heat transfer is in the range of 10.06…17.74 %, which is significantly lower than at temperatures of 35 and 45 °C (Fig. 4). The values of the convective component are higher than at other temperatures. So, at a medium pressure of 8 kPa, with an increase in the layer height from 0.01 to 0.04 m, the share of the convective flow decreases from 61.60 to 17.10 %. At 6 kPa, this indicator decreases from 63.18 to 19.44 %, and at 4 kPa – from 67.65 to 20.34 %. At the same time, it should be borne in mind that with an increase in the layer height, the intensity of drying decreases. The share of conductive heat transfer increases with the growth of the layer height. At 8 kPa, its values increase from 20.67 to 70.82 %, at 6 kPa – from 20.81 to 68.62 %, at 4 kPa – from 18.96 to 68.37 %. High intensity of the process is observed at material layer heights of 0.01…0.02 m, medium pressure of 4 kPa and heating temperature of 55 °C, and these drying parameters are considered optimum for Jerusalem artichoke tubers. The "convection: thermal conduction: radiation" ratio for a material layer height of 0.01 m as a percentage is 67.65: 18.96: 13.39. For 0.02 m, the numerical ratio of the heat transfer shares is 58.55: 29.39: 12.05.

The results of studies of heat transfer mechanisms during vacuum drying of liquid-viscous materials – camel and mare milk are described below.

The diagrams in Fig. 5 show the nature of the change in the share of each type of heat transfer during vacuum drying of camel and mare milk at a heating temperature of 40 °C, depending on the medium pressure of 10, 8, 6 kPa. It follows from the above data that as the degree of vacuum increases, the share of convective heat transfer for mare and camel milk decreases. So, at a pressure of 10 kPa, it is 79.49 and 75.76 %, respectively, at 8 kPa – 77.84 and 72.40 %, 6 kPa – 77.31 and 71.84 %. On the contrary, the share of heat transfer by radiation with an increase in the degree of vacuum from 10 to 6 kPa increases for mare milk from 12.66 to 17.89 %, for camel milk – from 16.53 to 22.79 %. The share of heat transfer by thermal conduction with increasing vacuum level decreases for mare milk from 7.85 to 4.8 %, for camel milk – from 7.71 to 5.36 %. In general, for the temperature regime of 40 °C and the pressure range of 6÷10 kPa, the quantitative ratio of each type of heat transfer (convection: thermal conduction: radiation) for mare milk is (%) 78.21: 6.23: 15.56, and for camel milk – 73.33: 6.55: 20.12.

Fig. 6 shows the change in the share of each type of heat transfer during vacuum drying of camel and mare milk at a medium pressure of 8 kPa, depending on the heating temperatures of 35, 40, 45 °C. The share of convection with an increase in temperature from 35 to 45 °C slightly decreases for mare milk from 79.14 to 75.89 %, for camel milk – from 78.02 to 70.25 %. The share of heat transfer by radiation increases for mare milk from 15.15 to 19.45 %, for camel milk – from 15.68 to 22.58 %. In contrast to these heat transfer methods, the change in the share of thermal conduction with increasing temperature is insignificant, is not linear, and has minimum values at a maximum heating temperature of 45 °C. For the temperature range of 35÷45 °C and medium pressure of 8 kPa, the quantitative ratio of each type of heat transfer (convection: thermal conduction: radiation) for mare milk is 77.62:5.8:16.91, and for camel milk – 73, 56:6.35:19.76.

6. Discussion of the results of the study of heat transfer mechanisms during vacuum drying of solid-moist and liquid-viscous materials

Fig. 2–6 revealed the nature of the change in heat transfer during vacuum drying of solid-moist and liquid-viscous materials proceeding under conditions of low and medium vacuum and moderate heating temperatures. On the heat transfer mechanism for vacuum drying of Jerusalem artichoke tubers, referring to Fig. 2–4, we can conclude the following:

– the share of radiation heat transfer practically doesn't depend on the vacuum level (in the investigated range of 4–8 kPa), but decreases with an increase in the heating temperature and the height of the material layer;

– the effect of convective heat transfer increases slightly with an increase in the heating temperature, but doesn't depend on the vacuum level, and with an increase in the layer height, the effect of convection decreases;

– the share of heat supplied by thermal conduction increases in direct proportion to the increase in the layer height, but an increase in the heating temperature in this range slightly affects its change;

– at material layer heights of 0.01…0.02 m, the convective component prevails in the heat flow, and at layer heights of 0.03…0.04 m, the thermal conduction component prevails. Here, the theory of the prevalence of conductive heat transfer in a solid material is confirmed [11];

– at a heating temperature of 35 °C, thermal conduction prevails (7 cases out of 12), at 55 °C – convection (7 cases out of 12), at 45 °C their values are the same (in 6 cases).

At the same time, the high intensity of the process is observed at material layer heights of 0.01 and 0.02 m, medium pressure of 4 kPa and heating temperature of 55 °C, and these drying parameters are considered optimum for Jerusalem artichoke tubers. The "convection: thermal conduction: radiation" ratio for a material layer height of 0.01 m as a percentage is 67.65:18.96:13.39. For 0.02 m, the numerical ratio of the heat transfer shares is 58.55:29.39:12.05. In this case, one should speak about the prevalence of the convective component.

By the results of the analysis of heat transfer mechanisms during vacuum drying of liquid-viscous materials on the example of camel and mare milk (Fig. 5, 6), the following conclusions can be drawn:

– the share of radiation heat transfer somewhat increases with a decrease in the pressure of the medium and an increase in the heating temperature (in the studied interval);

– convective heat transfer decreases somewhat with decreasing pressure and increasing temperature;

– the share of the flow provided by thermal conduction practically does not change with an increase in the heating temperature, but with a decrease in pressure, the share of thermal conduction somewhat decreases. This is also confirmed by the results of studies that an increase in vacuum reduces the effect of thermal conduction [6];

– during vacuum drying of liquid-viscous materials, heat is transferred mainly by convection, to a lesser extent by radiation and thermal conduction.

It follows from the latter formulation that the convective component is also dominant for vacuum drying of camel and mare milk. For the temperature regime of 40 °C and the pressure range of 6÷10 kPa, the quantitative ratio of each type of heat transfer (convection: thermal conduction: radiation) for mare milk is (%) 78.21:6.23:15.56, and for camel milk – 73.33:6.55:20.12.

The formulated conclusions give an idea of the mechanism of heat transfer that occurs during vacuum drying of Jerusalem artichoke tubers, crushed in the form of cubes, and camel and mare milk. The conclusions are valid for the range of medium pressures of 4÷8 kPa and heating temperatures of 35÷55 °C for Jerusalem artichoke tubers, the range of medium pressures of 6÷10 kPa and heating temperatures of 35÷45 °C for camel and mare milk. Obviously, the studied pressure range corresponds to the first type of heat and mass transfer [12], where molecular diffusion and convection take place. In this case, the nature of the criterion equations will be similar to the equations describing convective heat and mass transfer, which must be taken into account in engineering calculations and optimization of vacuum dryer operating modes.

It should be noted that the pressure range in the study is limited, although the range under study covers the region of low and medium vacuum. In further studies, the area of investigated pressures should be expanded towards an increase in the degree of vacuum, taking into account changes in the type of heat transfer.

7. Conclusions

1. The process of vacuum drying was studied under the following modes:

– for Jerusalem artichoke: medium pressure 4...8 kPa, heating temperature 35...55 °C, layer height 0.01...0.04 m;

– for camel and mare milk: medium pressure 6...10 kPa, heating temperature 35...45 °C, layer height 0.01 m.

The numerical values of the heat transfer components: convection, thermal conduction and radiation are experimentally determined, and their share in the total heat flux is determined.

2. Patterns of changes in heat transfer depending on medium pressure, heating temperature and height of the material layer were revealed. The high intensity of the process is observed at a height of the layer of crushed Jerusalem artichoke tubers of 0.01 and 0.02 m, medium pressure of 4 kPa and heating temperature of 55 °C. In this case, the convective component is predominant (0.01 m – 58.55 % and 0.02 m – 67.65 %). The share of thermal conduction (18.96 and 29.39 %) and radiation (13.39 and 12.05 %) is much lower. The mechanism of thermal conduction begins to dominate with an increase in the height of the material layer (0.03 and 0.04 m). The convective component is also dominant for vacuum drying of milk: at medium pressures of 6÷10 kPa and a temperature of 40 °C, its value for mare milk reaches 78.21 %, for camel milk – 73.33 %. The second most important is the share of radiation (19.45 and 22.58 %). Conductive heat transfer has the minimum indicators (5.66 and 6.17 %). The large values of the share of thermal conduction during drying of Jerusalem artichoke compared to milk are explained by the fact that heat transfer occurs inside the tubers due to conduction, and inside milk – due to convection. The studied pressure range corresponds to the type of heat and mass transfer when molecular diffusion and convection take place. In this case, the nature of the criterion equations will be similar to the equations describing convective heat and mass transfer, which must be taken into account in engineering calculations and optimization of vacuum dryer operating modes.

Conflict of interests

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

The manuscript has no associated data.

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