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IMPROVING THE EFFICIENCY OF DRYING EISENIA FETIDA BY USING A TECHNIQUE WITH INDUCED HEAT AND MASS TRANSFER

Nikolay Pogozhikh
Doctor of Technical Sciences, Professor*
Andrey Pak
Corresponding author
Doctor of Technical Sciences, Associate Professor*
E-mail: pak.andr1980@btu.kharkov.ua
Alina Pak
PhD, Associate Professor
Department of Marketing and Trade Entrepreneurship
Ukrainian Engineering Pedagogics Academy
Universitetska str., 16, Kharkiv, Ukraine, 61003
Andrii Sychov
PhD, Associate Professor
Department of Equipment and Engineering of Processing and Food Industries**
Tatiana Sychova
PhD, Associate Professor*
Maryna Sofronova
PhD, Associate Professor
Department of Higher Mathematics
National Technical University «Kharkiv Polytechnic Institute»
Kyrpychova str., 2, Kharkiv, Ukraine, 61002
*Department of Physics and Higher Mathematics**
**State Biotechnological University
Alchevskykh str., 44, Kharkiv, Ukraine, 61002

This paper substantiates the need to rationalize the drying process of such a vermitechnology object as Eisenia Fetida worms to utilize them as feed for industrial animal husbandry and poultry farming. This will contribute to improving the energy efficiency of vermitechnology application in the production of agricultural products.

A technique of drying with the effect of induced heat and mass transfer has been adapted for raw materials with a low amount of dry substances, which is a homogenate of worms. Two adaptation techniques are proposed: drying the homogenate in a heat and mass exchange module with artificially created obturators; drying a mixture of homogenate with grain bran with the spontaneous formation of obturators from raw materials.

Studies of various homogenate drying techniques have established that the longest duration of dehydration is achieved by convective drying technique. This is 1.2 times larger compared to the conductive technique and 2 and 3 times larger than drying with the effect of induced heat and mass transfer depending on the technique of obturator formation. It has been established that the final moisture content of dried products is the smallest for techniques involving the effect of induced heat and mass transfer. It is in 2...3 times less compared to convective and conductive techniques.

Drying with the effect of induced heat and mass transfer of mixtures with the following mass ratio of the homogenate to grain bran was investigated: 1:1; 2:1; 3:1. It was established that for a sample with a ratio of 3:1, the nature of the kinetics of drying is different from the typical kinetics for the effect of induced heat and mass transfer. The consequence is an increase in the duration of dehydration compared to samples of 1:1 and 2:1 by 1.3 times.

The results can be used in agriculture, namely, industrial animal husbandry, poultry farming, and vermitechnology

Keywords: effect of induced heat and mass transfer, Eisenia Fetida worms, thermostat obturator, drying of raw materials of animal origin, temperature kinetics

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1. Introduction

Reducing the cost of agricultural production is typically achieved by increasing the efficiency of the use of so-called man-made energy. However, more and more attention is paid to finding ways to solve this issue that are directly related to the use of a biological object and its waste products [1].

One of these ways is vermitechnology, aimed at preventing environmental pollution with waste products of farm animals. The use of vermitechnology makes it possible to dispose of waste, to increase soil fertility, to obtain fodder protein and pharmaceuticals [2]. Thus, one conditional unit of mass of manure obtained from industrial animal husbandry or poultry farming yields, during its processing by Eisenia Fetida worms, up to 0.6 conditional unit of mass of humus organic fertilizer. The remaining 0.4 conditional units of mass are converted into 0.1 conditional units of mass of worms and microorganisms and the energy of their vital activity.

It is important to note that Eisenia Fetida worms are a complete protein for industrial animal husbandry and poultry farming [3]. Vegetable protein makes up 90 % of the total balance of feed protein, and the remaining 10 % is high-grade animal protein. Moreover, it is these 10 % of animal protein that determine the effectiveness of the absorption of vegetable protein. In world practice, there are examples of the successful use of the Eisenia Fetida worm protein as an animal protein

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in animal and bird feed. It is applied in the form of flour, which is added as an additive to the feed.

Flour from these worms in its chemical composition is close to fishmeal [4]. It contains up to 60...65 % protein, up to 20 % carbohydrates, and up to 20 % fat. Among the amino acids contained in the flour from Eisenia Fetida worms, it is necessary to highlight especially valuable ones – lysine 8 %, methionine 3 %.

The technology for producing flour from Eisenia Fetida worms includes such a heat and mass transfer process as drying. Drying is a process that refers to high-energy-consuming processes. The presence of such a technological operation in the technological scheme entails an increase in the cost of the products received. Thus, the rationalization of the drying process will increase the energy efficiency of the use of vermitechnology in the production of agricultural products.

2. Literature review and problem statement

In drying technology, any object is systemic water and dry matter [5]. The Eisenia Fetida worms from this point of view consist of 35...40 % dry matter and 60...65 % of system water. That is, worms for drying technology are highly moist raw materials, which are considered a material with a low amount of solids or a high specific porosity [6]. There are a number of ways that implement the drying process of such raw materials and the technologies that provide them.

In production, two main techniques are used to dehydrate wet materials with a low amount of solids or high specific proportion.

The first technique is to use additional operations for the preliminary preparation of raw materials. So raw materials with high specific porosity are crushed and thus reduce the porosity [7], and then send such raw materials for drying. The result is energy efficient, however, due to grinding and increased processing time, the quality is significantly reduced. For drying raw materials with a low amount of solids, pressing is often used as a preliminary preparation [8] or centrifugation [9]. With the help of such additional operations, the amount of liquid in the feedstock is reduced, and, accordingly, the amount of solids per unit mass is increased. Next, such raw materials are dried. The liquid formed during pressing or centrifugation is disposed of or evaporated depending on the type of raw material and the value of the resulting liquid [10]. From the point of view of energy consumption for such techniques, they are also effective, but the quality of the products obtained, as a rule, is low. They apply such techniques for raw materials that do not contain nutrients that need to be preserved. Another way to increase the amount of solids in the feedstock is the operation of preliminary evaporation of the liquid, followed by drying the condensed raw materials [11]. This technique entails additional energy costs for the evaporation process, which reduces its economic attractiveness.

The second technique is to choose the technique of drying. Raw materials with high specific porosity or with a low amount of solids are usually dried by drying in a fluidized bed or by a vibrating drying technique [12]. Such methods make it possible to remove moisture from the raw materials, but the duration of the drying process is significant, and the temperature effect is high. This entails significant losses of thermolabile nutrients. Raw materials with a low amount of solids are dehydrated by evaporation at low pressure [13], sublimation drying [14], or spray drying [15].

The quality of products obtained by sublimation drying and drying at low pressure is high. However, the equipment to enable the moisture removal process is complex and the energy consumption is high. Therefore, the use of these techniques is cost-effective for raw materials with valuable thermolabile nutrients that must be preserved, widely used in pharmaceutical industries. They often use alternately different drying techniques or select different modes depending on the type of raw materials and quality requirements for the resulting product [16]. This technique obviously complicates the dehydration technology and requires additional costs to control external factors affecting the parameters of the heat and mass transfer process.

A common disadvantage of techniques and technologies that implement the process of drying wet materials with a low amount of solids or high specific variability is the additional capital investment in equipment. At the same time, the quality of the final product is often low.

One of the ways to avoid these shortcomings is to use a device operating using the effect of induced heat and mass transfer (InHMT) [17]. The InHMT effect is an «artificial» energy-technological process that does not spontaneously proceed but only under the condition of induction. The advantages of its use for heat and mass transfer are high energy efficiency.

Devices with the effect of InHMT are widely used for various raw materials of plant and animal origin [18]. However, there are restrictions on the use of these devices for raw materials with a low amount of solids or high specific porosity. This is due to a number of features of the InHMT effect, the physical mechanism of which remains insufficiently revealed. This suggests that it is expedient to conduct research on the nature of the InHMT effect under different types of its organization. The obtained results will expand the possibilities of using InHMT machines for drying wet materials with a low amount of solids or high specific porosity.

3. The aim and objectives of the study

The aim of this study is to determine the nature of the InHMT effect in the applied aspect of drying wet materials with high porosity or low volume of dry matter, which will help reduce energy and material costs for the production of Eisenia Fetida worm flour.

This will make it possible to improve the energy efficiency of agro-industrial production, namely vermitechnology.

To accomplish the aim, the following tasks have been set:

– to adapt the technique of dehydration using the InHMT effect for raw materials with a low amount of solids, which is a homogenate from Eisenia Fetida worms;

– to investigate the process of dehydration of the homogenate from the Eisenia Fetida worms, organized by various drying techniques: convective, conductive at reduced pressure, drying using the InHMT effect;

– to determine the rational ratio between the components of the raw material to be dried using the InHMT effect.

4. The study materials and methods

4. 1. The studied materials and equipment used in the experiment

The object of our study is the energy efficiency of the process of dehydration of the homogenate from Eisenia Fetida worms, taking into account the energy and material consumption of drying in various ways of raw materials with high porosity or low amount of solids.

The subject of the study is the process of dehydration of raw materials with high porosity or a low amount of solids by a drying technique using the InHMT effect.

The raw material for the current research is the homogenate from the Eisenia Fetida worms. The homogenate was prepared as follows. Live worms were kept in a calorimeter at a temperature of 3...6 °C for 24...48 hours to empty their intestines. Next, the worms were washed under running water and kept on sieves to drain its residues. After that, the raw materials obtained in this way were mechanically crushed to particles with a size of not more than 1...3 mm. Moisture content (the ratio of the mass of systemic water to the mass of dry substances) of such raw materials was 1.50...1.55 relative units.

Dehydration of the homogenate from Eisenia Fetida worms by convective technique was carried out in a laboratory drying cabinet at a drying agent temperature of 98...100 °C. Raw materials were placed in a drying chamber on sheets with a perforated surface. The diameter of the perforation holes did not exceed 0.2 mm. The thickness of the raw material layer was 10 mm. The speed of movement of the drying agent relative to the surface of the raw material was 10...15 m/s.

We studied the process of dehydration of the homogenate from Eisenia Fetida worms, organized by a conductive drying technique at reduced pressure, in a laboratory vacuum drying cabinet manufactured by TOV NVP Ukrorgsintez (Ukraine). The raw materials were placed on sheets with a layer 10 mm thick and placed in the working chamber of the drying cabinet. Next, the raw materials were preheated to a temperature inside the layer of 98...100 °C, and then air was pumped out of the working chamber of the drying cabinet to a pressure of 10...20 kPa.

The drying of raw materials using the InHMT effect was organized in a special heat and mass exchange module, the general view of which is shown in Fig. 1.

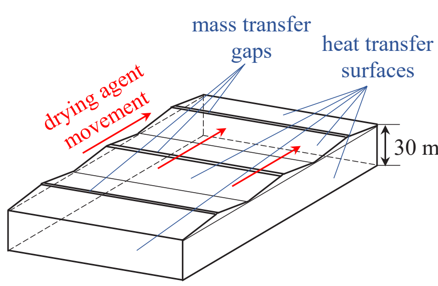

Fig. 1. General view of the heat and mass transfer module for drying using the effect of induced heat and mass transfer

The heat and mass exchange module is made of vaportight material with high thermal conductivity. As such material, sheets with a thickness of 1 mm made of aluminum alloy, approved for use in the food industry, were applied. The heat and mass exchange module was placed in the drying chamber to enable the movement of the drying agent relative to the mass exchange gaps at a speed of 10...15 m/s. The temperature of the drying agent was 98...100 °C.

4. 2. Procedures used in the study of the drying process of the homogenate from Eisenia Fetida worms

During the dehydration of the homogenate from the Eisenia Fetida worms by each technique, we recorded the temperature of the raw material layer and periodically determined the mass. According to the established mass, the current moisture content w of the raw materials was calculated from the formula:

$$w=(m-m_{s.s.})/m_{s.s.}, \qquad (1)$$

where m is the current mass; $m_{s.s.}$ – mass of solids.

The temperature of the raw material and the temperature of the drying agent were measured using thermocouples. Registration of signals from thermocouples was carried out using analog-digital and digital-analog converters made by DCON Utility (USA).

Dehydration of raw materials was continued until the raw material reached the temperature of the drying agent (convective drying technique), the temperature of the drying cabinet (conductive drying technique), or the final temperature of the calorimeter (drying using the InHMT effect). This temperature for each of the techniques was 98...100 °C.

The necessary and sufficient conditions for the organization of the InHMT effect are given in detail in [17]. It is possible to judge the «launch» of the InHMT effect based on the nature of the temperature kinetics at different points inside the thermostat, which is obtained by registering a signal from thermocouples.

The «launch» of the InHMT effect on the thermogram corresponds to a drop in body temperature. After removing the liquid phase inside the thermostat, the body temperature begins to approach the temperature of the thermostat again. The InHMT effect ends under the condition that the mass of the liquid in the thermostat is zero. This means that the system has reached equilibrium.

5. Results of studying the process of dehydration of the homogenate from Eisenia Fetida worms

5. 1. Adaptation of the dehydration technique with the effect of induced heat and mass transfer for raw materials with a low amount of solids

The main necessary requirement for the implementation of the InHMT effect is the presence of the continuity of the gas medium at the partial pressure of the liquid vapor inside the thermostat. Provided that this parameter is in order, the effect of InHMT is possible even under the condition of spatial separation of solids and liquids.

Obturators are used to meet this requirement. Obturators are parts of a thermostat that create a defined resistance, both to the flow of air moving relative to the outer surface of the obturator and its fluctuations, and to the internal environment. The filtration properties of the obturator should be such that the total pressure of the surrounding gas environment is balanced by the total pressure of the internal gas environment. In this case, the boundary of the separation between these media should be in the volume of the obturator.

There are two ways to build an obturator. The first technique is to choose a suitable capillary porous material that fills the gap in the thermostat wall and determines its filtration properties. The second way to build an obturator is its spontaneous formation from raw materials that are subject to technological processing using the InHMT effect.

Based on experimental studies and theoretical calculations, the effective filtration coefficient of the obturator necessary for the implementation of the InHMT effect is selected from the range from $2\cdot10^{-2}$ to $3\cdot10^{-2}$ m/s. It is possible to achieve the required value of the filtration coefficient in one of the described techniques.

Since the homogenate from the Eisenia Fetida worms is a raw material that has a low amount of solids, the spontaneous formation of an obturator does not occur from it.

Based on this, obturators should be made artificially. It is proposed to use synthetic felt and stainless-steel filter mesh as a material for artificially building obturators. The layout of the synthetic felt and filter mesh in the obturator are shown in Fig. 2.

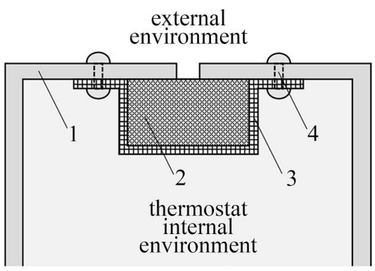

Fig. 2. General view of an artificially built obturator: 1 – thermostat wall; 2 – synthetic felt; 3 – stainless-steel filter mesh; 4 – fasteners

Synthetic felt of appropriate thickness and cross-section creates an energy barrier between the external and internal environment of the thermostat. This provides for the continuity of the gas medium by the partial pressure of the liquid vapor inside the thermostat. Metal filter mesh protects the felt from contamination and limits the change in its volume due to swelling in the case of moistening of this material.

Thus, the use of an artificial obturator makes it possible to provide one of the necessary conditions for the «launch» and «progress» of the InHMT effect during the drying of raw materials with high porosity or a low amount of solids. And, precisely, such obturators enable the continuity of the gas medium inside the thermostat according to the partial pressure of the liquid vapor.

In order to build obturators in the second way, that is, for obturators to form spontaneously from raw materials during the dehydration process, it is necessary to increase the amount of solids in the feedstock. Increasing the amount of solids for such raw materials is a necessary operation. With this technique for building obturators, the heat and mass exchange module is filled with wet raw materials so that the raw material fits tightly to its walls and gaps. At the beginning of the process, part of the raw material near the gap dries first, thus creating a thermostat obturator. At the same time, the volume of raw materials should not decrease during dehydration by more than 10...15 %. In the case of greater shrinkage, the raw material is separated from the gap and ceases to perform the functions of an obturator – the effect of InHMT «breaks».It is possible to increase the amount of solids in raw materials by adding to the homogenate either an inert material (for example, Teflon balls), or a material that will be a component in the final product. Inert material must be removed from the obtained dried products, which entails the introduction of an additional operation into the technological scheme for obtaining flour from Eisenia Fetida worms, and, as a result, additional costs.

At the same time, it should be noted that flour from worms, as a rule, is not used in its pure form, but is added as a protein additive to feed for industrial animal husbandry or poultry farming. Based on this, the introduction of such components of most feed, such as, for example, grain bran, can be partially divided. The first part should be applied to increase the amount of solids in the homogenate, and the second part, respectively, during the manufacture of feed, taking into account the mass of the first part. This technique makes it possible to avoid the operation to remove additional materials, as well as to implement the drying process using the InHMT effect.

5. 2. Investigation of the drying process of the homogenate from Eisenia Fetida worms by different techniques

We compared the drying efficiency of the homogenate from Eisenia Fetida worms made by different techniques according to the obtained temperature kinetics and drying kinetics. At the same time, the process of dehydration of the homogenate was organized by a convective technique, conductive at reduced pressure, by drying using the InHMT effect. Drying with the effect of InHMT was carried out in two ways – subject to the use of artificial obturators and subject to their spontaneous formation in raw materials.

The kinetics of drying and temperature kinetics obtained in this case are shown in Fig. 3, 4, respectively. On drying kinetics, the current moisture content and the current duration of the dehydration process were normalized, respectively, for the maximum moisture content and for the maximum duration of the process. On the kinetics of temperature, only the current duration was normalized for the maximum duration of the drying process. Normalization was carried out in order to represent the results more clearly.

The duration of convective drying of the Eisenia Fetida worm homogenate with its initial moisture content of 1.5 relative units is 180 min. With the same initial moisture content of the feedstock, the duration of conductive drying at a reduced pressure is 150 minutes, and for drying with InHMT using artificial obturators – 90 minutes. For the technique of dehydration with the effect of InHMT, subject to the spontaneous formation of obturators from raw materials, the starting raw materials were mixed with grain bran. For the kinetics of drying shown in Fig. 3 (curve 4), the homogenate was mixed with grain bran in a ratio of 1:1. The initial moisture content of such a mixture was 0.75 relative units. The duration of the process is 60 minutes.

It is important to note that the final moisture content of the dehydrated homogenate at convective drying technique is in the range of 0.18...0.19 relative units, with a conductive drying technique at reduced pressure – 0.14...0.15 relative units. At the same time, for dehydration with the effect of InHMT, the final moisture content of dehydrated raw materials is 0.06...0.07 relative units.

Fig. 3 also shows that the kinetics of drying using the InHMT effect (curves 3, 4) are fundamentally different from classical kinetics when using convective and conductive drying techniques. The kinetics of drying with the effect of InHMT have a typical S-shaped character, according to which they understand whether the InHMT effect was launched or not.

The temperature kinetics inside the raw material layer are also special (Fig. 4). With both convective and conductive drying, the temperature rises monotonously, which indirectly indicates a monotonous decrease in the drying rate due to the maximum value. Obviously, the first removed is that part of the systemic water of the raw material the molecules of which have a lower binding energy with dry matter molecules. Accordingly, the speed of its removal is greatest. As we move to the removal of systemic water with greater energy of interaction of its molecules with dry substances of raw materials, the drying rate decreases monotonously.

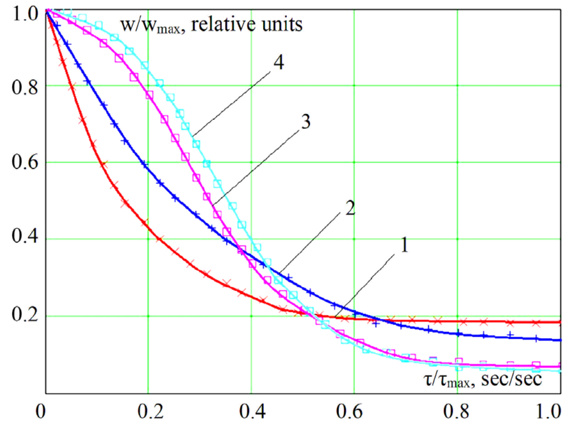

Fig. 3. Kinetics of drying raw materials during dehydration using various techniques: 1 – convective; 2 – conductive at reduced pressure; 3 – drying with the effect of induced heat and mass transfer using artificial obturators; 4 – drying with the effect of induced heat and mass transfer, subject to self-active formation of obturators

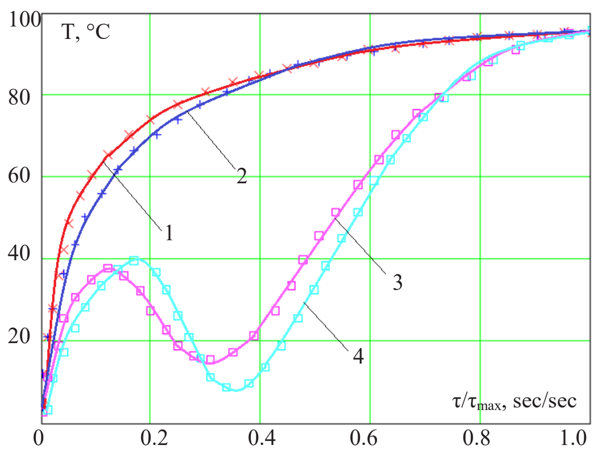

Fig. 4. Temperature kinetics inside the raw material layer during dehydration using different techniques: 1 – convective; 2 – conductive at reduced pressure; 3 – drying with the effect of induced heat and mass transfer using artificial obturators; 4 – drying with the effect of induced heat and mass transfer, subject to the spontaneous formation of obturators

For drying with the effect of InHMT, the temperature change inside the raw material layer is fundamentally different (curves 3, 4 in Fig. 4). The first stage of the dehydration process with the effect of InHMT is characterized by an increasing drying rate. At the beginning of the process, there is a gradual increase in speed due to the acquisition of solidity by the gas medium inside the thermostat. The establishment of the continuity of the gas medium entails a monotonous increase in temperature. If continuity is achieved, then it is possible to launch the effect of InHMT, which is accompanied by the effective dispersion of thermal energy for the transition of system water from a liquid to a gas state. Due to this intensive energy dispersal, the temperature of the raw material in the thermostat begins to decrease (curves 3, 4 in Fig. 4). The derivative of the temperature of the raw material over time acquires a negative sign. This nature of the kinetics of the temperature of raw materials is a feature of the course of the InHMT effect.

The temperature of the raw material decreases until the end of the liquid system water in the thermostat, which can enter the gas state at these pressures and temperatures. This point is the point of inflection of temperature kinetics, is the point of change of the sign of the raw material derived from the temperature over time. The InHMT effect ends. After that, the temperature of the raw material increases and reaches the value of the thermostat temperature.

5. 3. Investigation of the effect of the ratio between the components of raw materials on the drying process using the effect of induced heat and mass transfer

The course of the InHMT effect significantly depends on the physical properties of the raw materials in the thermostat. Based on this, it is necessary to investigate the effect of the ratio between the components of raw materials, provided that the mixture of homogenate from Eisenia Fetida worms with grain bran is dried, on the nature of dehydration using the InHMT effect.

The following mass ratios between the homogenate of worms and grain bran were investigated, respectively: 1:1; 2:1; 3:1. The initial moisture content of samples with a mass ratio of homogenate:grain bran was, respectively, equal to: for the sample 1:1 – 0.75 relative units; 2:1 – 1.0 relative units; 3:1 – 1.1 relative units.

The criteria for choosing a rational ratio between the mass of the homogenate from worms and grain bran were the initial moisture content and the duration of the raw material reaching the final moisture content, that is, the duration of the drying process using the InHMT effect.

Kinetics of drying samples with different ratios of raw material components are shown in Fig. 5.

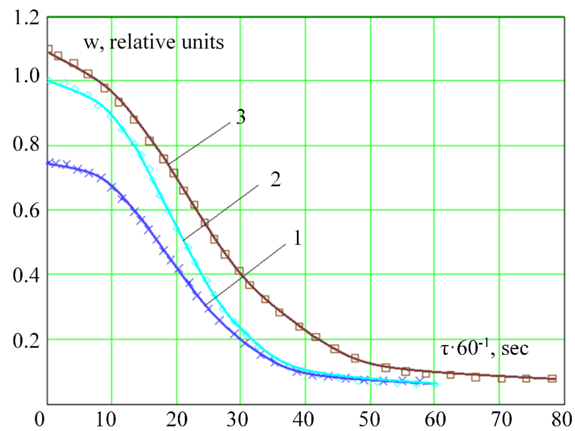

Fig. 5. Kinetics of drying with the effect of induced heat and mass transfer of raw materials with a mass ratio of components in the homogenate from worms:grain bran:
1 – 1:1 (50 % homogenate and 50 % grain bran);
2 – 2:1 (63 % homogenate and 33 % grain bran);
3 – 3:1 (75 % homogenate and 25 % grain bran)

These results indicate that for all three samples, the launch of the InHMT effect during dehydration is realized. All three dependences are S-shaped in nature, which indicates the presence of an extremum depending on the drying rate on the current moisture content. This proves the presence of an inflection on the drying kinetics.

However, it should be noted that as the amount of systemic water in the raw materials increases, the kinetics of drying (curve 3 in Fig. 5) approaches the kinetics of convective drying (curve 1 in Fig. 3). For a sample with a moisture content of 1.1 relative units (the ratio of components of the homogenate from worms:grain bran of 3:1), the area of increasing drying rate decreases. As a result, the intensity of the InHMT effect decreases. The result of this behavior of the dehydration process is an increase in the drying time to 80 minutes.

The comparison of curves 1 and 2 from Fig. 5 shows that they are typical for dehydration using the InHMT effect. It should be noted that the drying time of the sample with an initial moisture content of 0.75 relative units (50 % homogenate and 50 % grain bran) is the same as for a sample with an initial moisture content of 1.0 relative units (63 % homogenate and 33 % grain bran). The duration of dehydration for such samples is 60 minutes.

6. Discussion of results of studying the drying process of the homogenate from Eisenia Fetida worms

Four techniques of dehydration of homogenate from Eisenia Fetida worms were investigated: convective, conductive at reduced pressure, drying technique using the InHMT effect. The third technique was implemented in two ways: subject to the use of artificial obturators and subject to their spontaneous formation in raw materials.

The criteria for evaluating the effectiveness of various techniques were chosen as follows. The main factors for assessing energy efficiency were the initial moisture content of raw materials and the duration of the process of its dehydration as indirect indicators of energy and material consumption.

Since studies were conducted in view of the use of dried products as animal protein in animal and poultry feed, product quality was a secondary factor. The main attention regarding quality was paid to such a quality indicator as the final moisture content of dried products since this property is the initial one when obtaining flour from such raw materials.

Based on the duration of drying, the longest duration of dehydration of the homogenate from Eisenia Fetida worms is achieved by convective drying technique. At conductive technique at reduced pressure, the duration of dehydration is 1.2 times less compared to convective drying. For dehydration with the effect of InHMT, the drying process had, according to the technique of creating an obturator, 2- and 3-times shorter duration compared to convective. At the same time, if we compare it with the conductive technique at a reduced pressure, the drying time with the InHMT effect is 1.7 and 2.5 times less, respectively. In terms of the duration of the process of dehydration of the homogenate from Eisenia Fetida worms, techniques with an InHMT effect are more attractive.

An important advantage of drying techniques with the effect of InHMT is also the low final moisture content, which is 0.06...0.07 relative units. This is 2...3 times less compared to convective and conductive techniques. Such a low moisture content makes it possible to grind dried products without additional preparatory operations at low energy costs.

However, the initial moisture content in the three studied techniques is the same (convective, conductive at reduced pressure, with the effect of InHMT with artificial obturators) and is 1.5 relative units, and according to the technique of drying with InHMT at the spontaneous formation of obturators from raw materials is 0.75 relative units. This is 2 times less compared to the original moisture content in other techniques. The reason for the lower initial moisture content is an increase in the amount of solids in the raw materials due to the addition of dry substances of grain bran.

This result leads to an increase in the efficiency of the drying technique with the effect of InHMT with the spontaneous formation of obturators from raw materials. This can be done by finding a rational relationship between the homogenate of worms and grain bran. In this case, the search should be directed towards reducing the amount of applied grain bran.

Our studies of the drying process with the effect of InHMT for mixtures with a mass ratio between the homogenate from worms and grain bran of 1:1 (moisture content, 0.75 relative units); 2:1 (moisture content, 1.0 relative units); 3:1 (moisture content, 1.1 relative units), have established the following. The kinetics of drying samples with a component ratio of 1:1 and 2:1 have a typical form for an InHMT drying process. The result of the full implementation of the effect is its stable duration of 60 minutes.

For a sample with a ratio of homogenate from worms: grain bran of 3:1, the nature of the drying kinetics is different from the typical kinetics for the InHMT effect. The reason is obviously a complication with the spontaneous formation of an obturator due to its high porosity and the deposition of the raw materials from which it is formed. The consequence of this is an increase in the duration of dehydration with an InHMT effect compared to other samples, by 1.3 times. It should be noted that the moisture content increased relative to the sample with a ratio of 2:1 by only 10 %.

Based on our result, the rational ratio between the homogenate of worms and grain bran should be considered, respectively, the ratio of 2:1. With this ratio, the nature of the dehydration process is close to the nature of the course of the InHMT effect. At the same time, the amount of homogenate is the largest among the studied component ratios in mixtures.

Thus, on the basis of our research, two techniques of drying Eisenia Fetida worms are proposed. Drying of such raw materials should be carried out in the form of a homogenate. The first technique is dehydration using the effect of InHMT homogenate from worms in a special heat and mass exchange module with an artificially made obturator made of synthetic felt and stainless-steel filter mesh.

The second technique involves pre-mixing the homogenate from worms with grain bran in a ratio of 2:1, respectively, and subsequent drying in a heat and mass exchange module to realize the InHMT effect.

The advantages of such techniques are as follows. First, it is low energy consumption compared to convective and conductive techniques. The reduction in energy consumption is due to the use of the InHMT effect for the effective dispersion of energy through the transition of system water from liquid to gas. The drying technique with the effect of InHMT makes it possible to reduce energy consumption by 30 %. Second, it is a low final moisture content, which is an important functional and technological property of dried products. Obtaining dried products with low moisture content of 0.06...0.07 relative units is the result characteristic of the effect used. Third, it is the simplicity of the equipment to enable the dehydration process of Eisenia Fetida worms with an InHMT effect. Equipment for ensuring the implementation of the effect in complexity does not significantly exceed the equipment for convective drying. At the same time, it should be noted the versatility of such equipment – it can be used both for convective dehydration technique and for dehydration using the InHMT effect.

The limitation of the study is the lack of adapted drying technological lines using the effect of InHMT for raw materials with a high specific porosity or a low amount of solids. The use of heat and mass exchange modules with artificial obturators requires additional operation to clean or replace the synthetical felt used in this case. Therefore, the prospects for further applied research are the adaptation of the heat and mass transfer module with artificial obturators to production requirements.

The disadvantage of the study is the following. Adapted drying techniques using the InHMT effect for raw materials with a low amount of solids, which is in a separate case a homogenate of Eisenia Fetida worms, are used on periodic devices. The construction of continuous devices for such raw materials at this stage is impossible due to the limited amount of theoretical data on the complex controllability of the InHMT effect.

7. Conclusions

1. The technique of drying using the InHMT effect has been adapted to raw materials with a low amount of solids, which are Eisenia Fetida worms. Two ways of adaptation are proposed. According to the first technique, in the heat and mass exchange module, obturators made of synthetic felt and stainless-steel filter mesh are used to realize the InHMT effect. According to the second technique, the homogenate of worms is mixed with grain bran before being placed in the mass exchange module in order to increase the solids for the possibility of spontaneous formation of obturators from raw materials.

2. Our studies of four techniques of dehydration of the homogenate from Eisenia Fetida worms have established the following. The longest duration of dehydration of the homogenate from Eisenia Fetida worms is achieved by convective drying technique. This is 1.2 times larger compared to the conductive technique at reduced pressure and 2 and 3 times larger than for drying with the effect of InHMT depending on the technique of formation of the obturator. It has been established that the final moisture content of dried products is the smallest for dehydration techniques using the InHMT effect and is 0.06...0.07 relative units. This is 2...3 times less compared to convective and conductive techniques. It is noted that from the point of view of the final moisture content of dried products and the duration of the process of dehydration of raw materials as indirect indicators of energy and material consumption, techniques with the effect of InHMT are more attractive.

3. The studies of the drying process with the effect of InHMT mixtures with different mass ratios of the homogenate from worms and grain bran have established the following. The kinetics of drying samples with a component ratio of 1:1 and 2:1 have a typical form for an InHMT drying process. For a sample with a 3:1 component ratio, the nature of the drying kinetics is different from the typical kinetics for the InHMT effect. The consequence is an increase in the duration of dehydration compared to samples with ratios of 1:1 and 2:1 by 1.3 times. It is noted that the rational ratio between the homogenate with worms and grain bran should be a ratio of 2:1. With this ratio, the nature of the process is close to the nature of the InHMT effect, and the amount of homogenate is greater among the studied ratios.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

Manuscript has no associated data.

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