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Research of the energy parameters of the vibro-ozonation complex

Abstract. *In the system of technological operations of post-harvest processing of grain, the most important place belongs to drying. High-quality drying not only ensures the storage of the harvested crop, prevents its loss, but in some cases also improves the quality of the finished product. It is at this stage that up to 80% of all the energy of the post-harvest processing of grain is spent, and the useful use of energy in the grain dryers is up to 40…45%. The direction of improvement of grain drying technologies is: reduction of energy costs for moisture removal, ensuring environmental safety of the dried product, development of highly efficient grain drying equipment. A significant intensification of the grain drying process can be achieved by using the vibration effect on the processed material with simultaneous treatment with ozone as part of the drying agent, which additionally reduces the energy costs of the operation and allows obtaining a high-quality final material. The energy parameters of the developed vibro-ozonation complex, depending on the mode parameters of the studied process of drying grain raw materials, were experimentally investigated in the article.*

Streszczenie. *W systemie operacji technologicznych pozbiorczej obróbki ziarna najważniejsze miejsce zajmuje suszenie. Wysokiej jakości suszenie nie tylko zapewnia przechowywanie zebranego plonu, zapobiega jego utracie, ale w niektórych przypadkach poprawia również jakość gotowego produktu. To właśnie na tym etapie zużywa się do 80% całej energii na pozbiorczą obróbkę ziarna, a użyteczne wykorzystanie energii w suszarniach zbożowych sięga 40…45%. Kierunkiem doskonalenia technologii suszenia ziarna jest: obniżenie kosztów energii na odwilgocenie, zapewnienie bezpieczeństwa ekologicznego suszu, rozwój wysokowydajnych urządzeń do suszenia ziarna. Znaczne zintensyfikowanie procesu suszenia ziarna można uzyskać poprzez wykorzystanie efektu wibrowania obrabianego materiału przy jednoczesnym działaniu ozonu jako składnika suszenia, co dodatkowo obniża koszty energetyczne operacji i pozwala na uzyskanie wysokiej jakości materiału końcowego . W artykule zbadano eksperymentalnie parametry energetyczne opracowanego kompleksu wibro-ozonowania w zależności od parametrów modowych badanego procesu suszenia surowców zbożowych.* (***Badania parametrów energetycznych kompleksu wibro-ozonowania***)

Keywords: grain raw materials, drying, vibration, ozone, vibro-ozonating complex, ozone concentration, vibration acceleration
Słowa kluczowe: ziarno, wibro-ozonowanie..

Introduction

Drying is one of the most important stages of grain preparation for storage in agricultural production. Currently, the convective drying method is quite widely used to perform this technological process. But along with its advantages, this method has a number of significant disadvantages, one of the significant of which is significant energy consumption. In this regard, scientific search for the development of ways and methods of reducing the energy intensity of the convective method of processing is being carried out quite intensively [1].

The main direction of improvement of drying technologies is: reduction of energy costs for moisture removal, ensuring environmental safety of the dried product, development of highly efficient grain drying equipment.

Effective methods of intensifying the drying of grain raw materials are the introduction of ozonation technology in combination with the vibration effect on the processed raw materials.

Ozone intensifies the speed of grain drying due to the direct chemical and biochemical effect on agricultural raw materials, improves the movement of moisture from the inner layers and heat and mass exchange in the drying process as a whole.

When using ozone, the saving is about 89 kg of conventional of fuel per ton of raw materials received.

Drying with the use of ozone has an antibacterial effect and increases grain quality indicators, prevents self-heating processes, creates the necessary state of rest during the storage period, and preserves the volume of the processed material. The need for grain pickling disappears and there is an opportunity to minimize energy costs for the drying process.

The peculiarity of the use of ozone is that it does not lead to the formation of harmful by-products, since ozone decomposes into atomic oxygen [2].

The vibrational effect on the grain during its drying, in turn, ensures the uniformity of material processing, preventing the occurrence of local overheating zones due to the constant movement of raw materials.

Therefore, the introduction of new methods of drying grain raw materials through the development and research of the vibro-ozonation complex, in which the processed material is in constant oscillating motion, in combination with ozonation technology, is a promising direction in the development of grain drying equipment.

Analysis of literary sources and problem statement

The usefulness and relevance of the use of vibration technologies in the drying process are highlighted in works [3, 4]. Works [5, 6] are devoted to the theoretical and experimental research of the drying process of specific agricultural raw materials. The results of the application of physical effects in order to intensify the process of drying and further storage of agricultural products are given in works [7, 8]. A detailed review and classification of vibrating and drying equipment is carried out in works [9, 10]. In [11], the features of the effect of the ozone-air mixture on the characteristics of grain raw materials during drying, depending on the concentration of ozone, drying time, etc., are given in detail.

The question of increasing the energy efficiency of the grain drying process and the study of energy parameters of drying machines studied in papers [12–24].

Purpose and tasks of research

After analyzing the works [3-24], it can be established that:

- existing grain dryers work inefficiently, they are bulky, metal- and energy-intensive, difficult to maintain and repair, and have a high cost;
- increasing the energy efficiency of the drying process does not decrease, but on the contrary increases due to a sharp increase in energy prices;
- the study of the energy parameters of drying machines that use the vibration effect on the processed material with simultaneous treatment with ozone as part of the drying agent for the process of drying grain raw material has not been sufficiently studied.

Therefore, the purpose of the research is to determine the energy parameters of the vibro-ozonation complex intended for drying grain raw materials, which is an actual scientific and technical task.

Presentation of the main material of theoretical research

The energy parameters of the vibro-ozonation complex include electric power, which is spent on heating the drying agent with the help of electric elements (shades) N_1; the power consumed by the electric motor of the drive of the unbalanced shaft N_2; the power consumed by the electric fan drive motor N_3 and the electronic ozone synthesis device N_4.

The electric power that is spent on heating the drying agent with the help of electric elements (shades) N_1 (kW) is determined by the formula:

(1) $$N_1 = k \cdot \left(\frac{Q}{t} + P_{t.p.l} \right) \cdot 10^{-3};$$

where k – the power reserve estimation coefficient (k = 1.2...1.3 can be taken); Q – the total amount of heat needed to ensure the thermal process, J; t – duration of the thermal process, s; $P_{t.p.l.}$ – total power of heat loss, W.

The power consumed by the electric motor of the drive of the unbalanced shaft N_2 (kW) is determined by the formula:

(2) $$N_2 = \frac{M \cdot n}{9550};$$

where M – torque, Nm; n – the rotation frequency of the electric motor shaft, rpm.

The power consumed by the N_3 fan drive electric motor (kW) is determined by the formula:

(3) $$N_3 = \frac{9.81 \cdot L_F \cdot H}{3600 \cdot \eta_F \cdot \eta_T};$$

where L_F – fan performance, m^3/h; H – total pressure, Pa; η_F – efficiency of the fan (it is possible to accept η_F = 0.4...0.6); η_T – transmission efficiency (it is possible to accept η_T = 0.85...0.99).

The power consumed by the electronic N_4 ozone synthesis device (kW) is determined by the formula:

(4) $$N_4 = 4fC_d e_0 \left(e_{max} - \frac{C_a}{C} e_0 \right) \cdot 10^{-3};$$

where f – the current frequency, Hz; C_d – dielectric capacity, F; C_a – the capacity of the discharge gap, F; C – average installation capacity, F; e_0 – discharge potential through the gap, F; e_{max} – the maximum voltage of the current passing through the electrodes, V.

The main criterion for the energy characteristics of the vibro-ozonation complex is the energy consumption for the drive of the vibro-ozonation complex N, kW·h, which is characterized by the influence of the four most important factors that determine the kinetics of this treatment: vibration acceleration a, m/s^2 as a complex parameter of the dynamic state of the system; the temperature of the drying agent T, °C; concentration of ozone N_{O3}, mg/m^3, processing time t, min:

(5) $$N = f(a, T, N_{O3}, t).$$

Experimental equipment

For the implementation of high-quality drying of grain raw materials, an experimental model of the vibro-ozonating complex was designed and manufactured (Fig. 1), in which the material being processed is subjected to vibration, which increases and renews the heat exchange surface [15, 25]. As a result, there is an intensive removal of moisture, increasing the drying rate. The drying process takes place evenly throughout the layer, without causing local overheating of the material. The technical characteristics of the experimental model of the vibroozone complex are presented in Table 1.

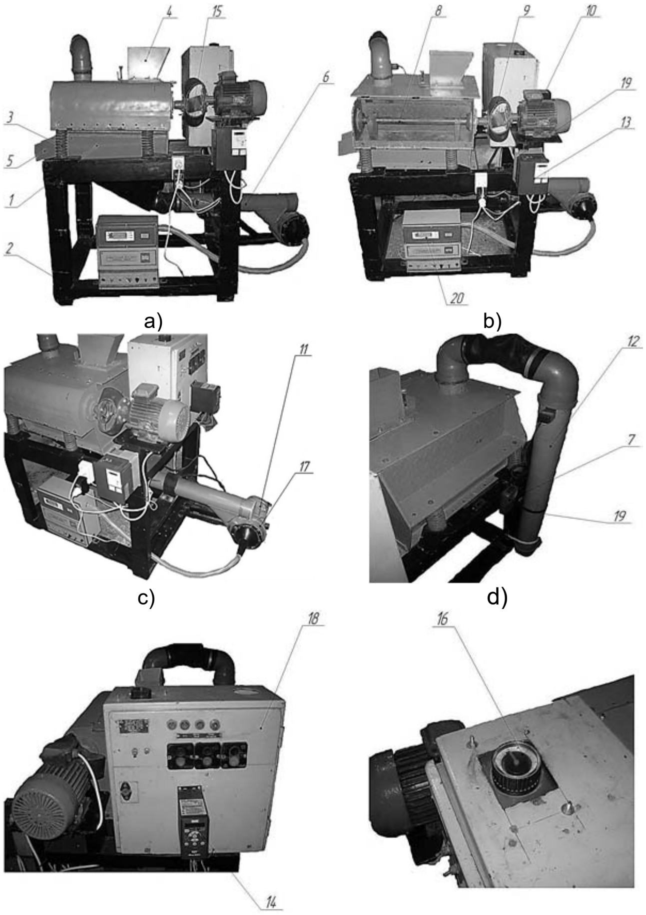

Fig. 1. Experimental model of vibroozonating complex: a, b – front view; c, d, e – side view; f – view from above; 1 – U-similar chamber; 2 – rack; 3 – springs; 4, 5 – loading and unloading trays; 6, 12 – respectively inlet and outlet ducts; 7 – thermal anemometer; 8 – unbalance shaft; 9 – elastic coupling; 10 – unbalance shaft drive electric motor; 11 – fan drive electric motor; 13, 14 – frequency converters; 15 – thermostat; 16 – time relay; 17 – fan; 18 – control block; 19 – moisture meters; 20 – electronic ozone synthesis device.

Vibro-ozonizing complex (see Fig. 1) is a hermetic U-similar chamber mounted on the rack with the help of springs. The chamber contains a loading and unloading trays, as well as air duct for the withdrawal of the spent drying agent. On the side of the chamber there is a shaft with two unbalances, which is driven into rotation through an elastic coupling by means of a three-phase electric motor.

In the lower part of the chamber there is an air duct with electric heating elements, through which the heated air and ozone generated by the ozonator enter, and is supplied by a fan using an electric motor.

a) b)

Fig. 2. Electronic ozone synthesis device: a – general form; b – ozone synthesis working chamber.

Table 1. Technical characteristics of the experimental model of the vibroozone complex

Index	Value
Installed total electrical power, kW: – power of the unbalance shaft drive electric motor, kW – power of the fan drive electric motor, kW – power of the heating electric elements, kW – power of electronic ozone synthesis device, kW	5 2.2 0.75 2 0.25
Unbalance shaft drive electric motor rotation frequency, rpm.	to 1500
Fan electric motor rotation frequency, rpm.	to 3000
Drying agent temperature, °C	to 75
Ozone concentration in the ozone-air mixture, mg/m^3	to 18
Drying agent rate, m/s	to 5
Oscillation amplitude of the drying chamber, mm	0.5… 7.5
Productivity of the vibroozonating complex for dry grain raw materials, kg/hr.	to 25
The mass of vibroozone complex, kg	265
The mass of drying chamber, kg	95
Vibroozone complex dimensions (length × width × height), mm	1700× 970× 1300
Drying chamber volume, m^3	0.06

As a drying agent, a mixture of heated air and ozone of a certain concentration, generated by a corona discharge in an electronic ozone synthesis device, is used (Fig. 2), the electrical circuit diagram of the power of which is built on the basis of a quasi-resonant converter.

The principle of operation of the complex is that the drying agent, which consists of heated air and ozone of a certain concentration, is fed by a fan mounted on the rack into a U-similar hermetic chamber in which the grain raw material is located. At the same time, the electric drive of the unbalanced shaft is turned on. The drying agent, passing through the grain layer and removing a certain percentage of moisture, enters the outlet air duct, through which it is removed from the drying chamber.

The results of the experimental study

During the experimental studies of the developed vibro-ozonation complex, such energy parameters were studied as: electric power, which is spent on heating the drying agent with the help of electric elements N_1; the power consumed by the electric motor of the drive of the unbalanced shaft N_2; the power consumed by the electric fan drive motor N_3 and the electronic ozone synthesis device N_4.

In fig. 3 shows the change in power consumption by electric heating elements depending on the temperature of the drying agent at a speed of movement of the drying agent of 1.5 m/s.

The equation, which was obtained on the basis of regression analysis of experimental data on changes in power consumption by electric heating elements depending on the temperature of the drying agent (see Fig. 3), has the form:

(6) $$N_1 = -0.8209 + 0.0309 \cdot T.$$

It can be seen from the given dependence that with the increase in the temperature of the drying agent T, the consumed power N_1 by the heating electric elements increases practically according to a linear law.

Also, during the analysis of the energy characteristics of the investigated vibro-ozonation complex, an increase in the power consumption of the electric motor of the unbalanced shaft drive was found depending on the total loading volume of the drying chamber, which at an operating angular velocity of ω = 90 rad/s is: N_2 = 480 W at 75% loading (Fig. 4); N_2 = 450 W at 50% load (Fig. 5).

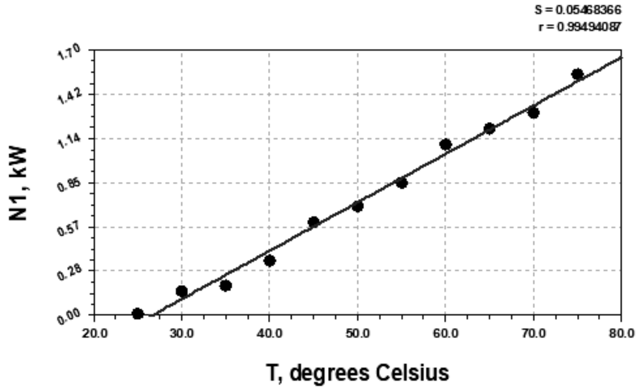

Fig. 3. Change in power consumption by electric heating elements depending on the temperature of the drying agent

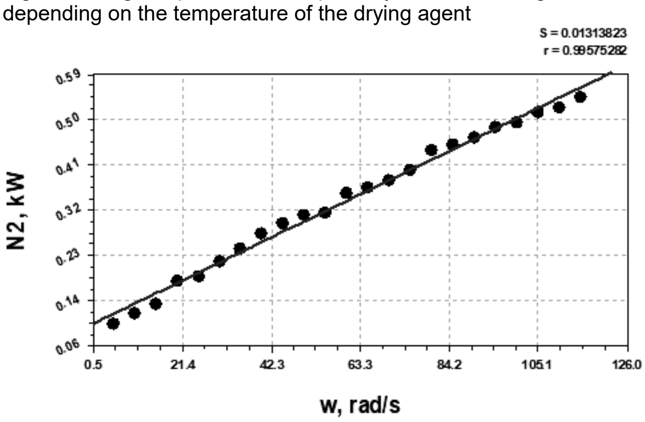

Fig. 4. Change in power consumption by the electric motor of the unbalance shaft drive depending on the angular velocity and degree of technological loading of the drying chamber when loading 75% of the full volume of the chamber

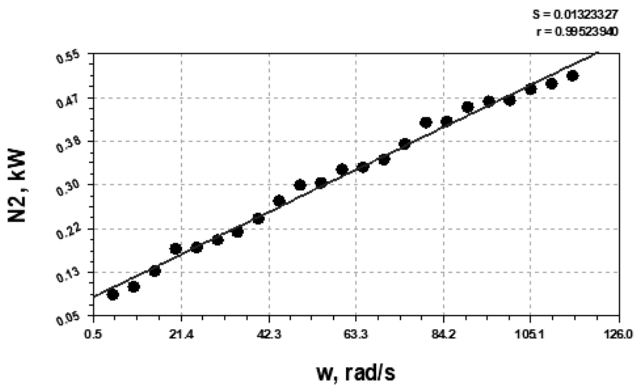

Fig. 5. Change in power consumption by the electric motor of the unbalance shaft drive depending on the angular velocity and degree of technological loading of the drying chamber when loading 50% of the full volume of the chamber

The equations obtained on the basis of the regression analysis of experimental data on the change in power consumption by the electric motor of the drive of the unbalanced shaft depending on the angular velocity and the degree of technological loading of the drying chamber are as follows:

- when loading 75% of the full volume of the chamber (see Fig. 4)

(7) $$N_2 = 0.0982 + 0.0040 \cdot \omega;$$

- when loading 50% of the full volume of the chamber (see Fig. 5)

(8) $$N_2 = 0.0838 + 0.0038 \cdot \omega.$$

When determining the energy characteristics of the vibro-ozonation complex, changes in the consumed power were studied depending on the frequency of rotation of the electric motor of the fan drive (Fig. 6).

From the experimentally obtained curve, it can be concluded that with an increase in the frequency of rotation of the electric motor, the power consumed by it increases. In addition, at the maximum revolutions of the electric motor n = 3000 rpm, the power consumed by it is N_3 = 0.115 kW at a speed of the drying agent of 3 m/s and a load of 50% of the full volume of the drying chamber and at a speed of the drying agent of 2.5 m/s and a load of 75% of the full volume volume of the drying chamber.

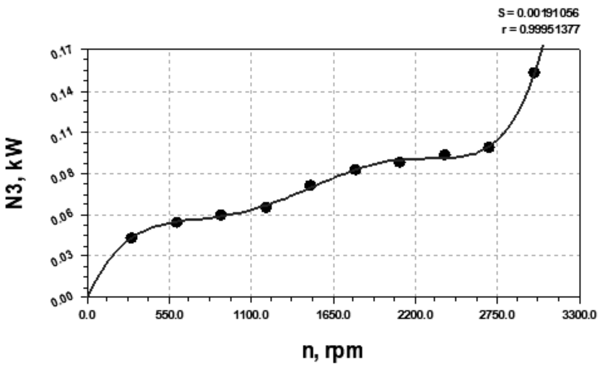

Fig. 6. Dependence of the change in the consumed power of the fan drive electric motor on the rotation frequency

The equation obtained on the basis of the regression analysis of the experimental data on the change in the consumed power of the electric motor of the fan drive depending on the rotation frequency (see Fig. 6) has the form:

(9) $$N_3 = 5.1419 \cdot 10^{-5} + 0.0002 \cdot n - 3.4807 \cdot 10^{-7} \cdot n^2 + 2.5394 \cdot 10^{-10} \cdot n^3 - 6.5128 \cdot 10^{-14} \cdot n^4 - 2.8901 \cdot 10^{-18} \cdot n^5 + 2.4095 \cdot 10^{-21} \cdot n^6.$$

In fig. 7 shows the change in the power consumed by the electronic device for the synthesis of ozone N_4 depending on the concentration of ozone N_{O3}, which it provided.

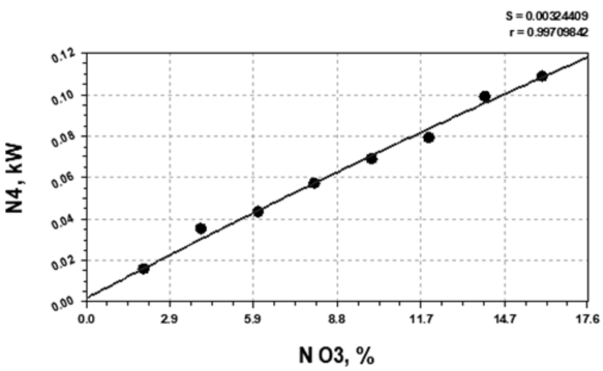

Fig. 7. Change in power consumed by an electronic ozone synthesis device depending on the ozone concentration it provided

As can be seen from the experimentally obtained curve, with an increase in the concentration of ozone N_{O3}, the consumed power of N_4 increases, practically, in direct proportion according to a linear law.

The equation obtained on the basis of the regression analysis of experimental data on the change in power consumed by an electronic ozone synthesis device depending on the ozone concentration provided by it (see Fig. 7) has the following form:

(10) $$N_4 = 0.0020 + 0.0072 \cdot N_{O3} - 3.6255 \cdot N_{O3}^2.$$

Based on the determined energy characteristics of the developed vibro-ozonation complex, the dependence of the total energy consumption N on the duration of processing t without ozone as part of the drying agent (Fig. 8) and with ozone as part of the drying agent (Fig. 9) was obtained.

The equations obtained on the basis of regression analysis of experimental data on changes in total energy consumption by the developed machine have the following form:

- without ozone in the drying agent (see Fig. 8)

(11) $$N = 0.0080 + 0.0127 \cdot t + 0.0001 \cdot t^2 - 7.3653 \cdot 10^{-7} \cdot t^3;$$

- with ozone as a drying agent (see Fig. 9)

(12) $$N = 0.0196 + 0.0086 \cdot t + 0.0002 \cdot t^2 - 8.9962 \cdot 10^{-7} \cdot t^3.$$

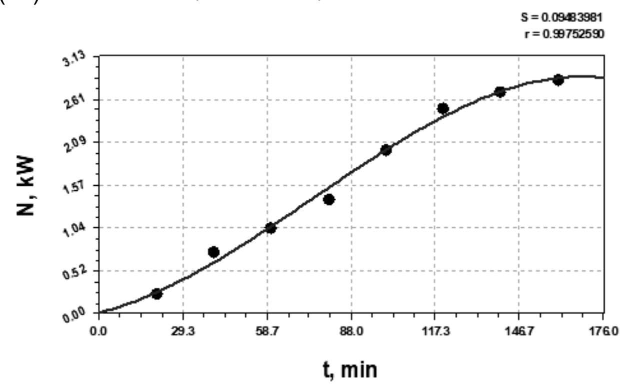

Fig. 8. Change in total energy consumption of the developed machine without ozone as a drying agent

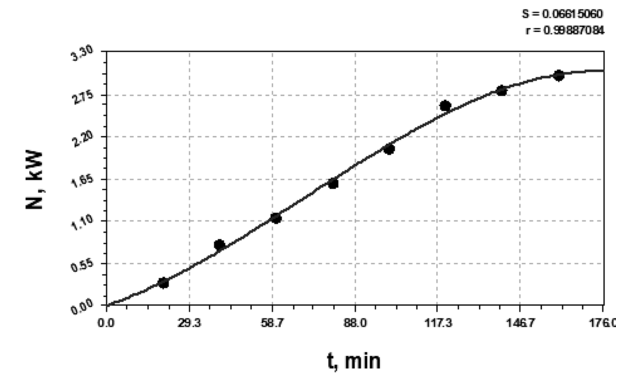

Fig. 9. Change in total energy consumption of the developed machine with ozone as a drying agent

Analysis of fig. 8 and fig. 9 testified that the specific energy consumption per unit of finished products with a moisture content of 14% at an initial moisture content of 20% is: using classical technology with the supply of a heating agent at a temperature of 50 °C with a treatment duration of 240 min – 112.93 W·h/kg or 18.82 W·h/kg per 1% of evaporated moisture (406.54 kJ/kg or 67.75 kJ/kg per 1% of evaporated moisture); for the use of complex thermophysical influence with a treatment duration of 160 min – 91.01 W·h/kg or 15.16 W·h/kg per 1% of evaporated moisture (327.63 kJ/kg or 54.6 kJ/kg per 1% of evaporated moisture).

After processing the experimental data in the statistical environment "STATISTICA 10.0", the coefficients of the complex equation of the multiple regression of energy consumption for the drive of the vibro-ozonation complex depending on the vibration acceleration of the chamber, the temperature of the drying agent, the concentration of ozone and the processing time were obtained:

$$N = 11.828 - 0.005 \cdot a - 0.303 \cdot T - 0.335 \cdot N_{O3} - 0.011 \cdot t + 0.001 \cdot a^2 + 0.003 \cdot T^2 + 0.01 \cdot N_{O3}^2 + 0.001 \cdot N_{O3} \cdot t. \quad (13)$$

Also, based on the obtained experimental data, a Pareto map of effects was constructed to assess the influence of factors on the energy consumption of the developed vibro-ozonation complex (Fig. 10).

According to the obtained Pareto map, the energy consumption of the developed vibro-ozonation complex is most affected by the processing time t and the temperature of the drying agent T.

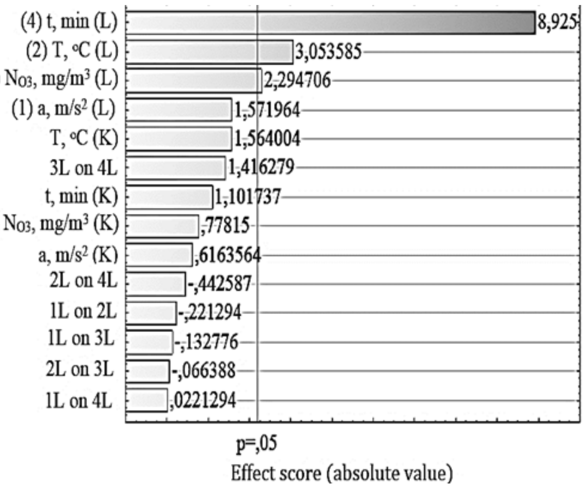

Fig. 10. Pareto map of effects for assessing the influence of factors on the energy consumption of the developed vibro-ozonation complex

Therefore, the qualitative characteristics of the drying process acquire their rational values at the final moisture content of grain raw materials of 13...14% and energy consumption for the drive of the vibro-ozonation complex of 3...3.2 kW.

Conclusions

1. A vibroozonizing complex was proposed and developed for the implementation of the technological process of drying grain raw materials, in which the processed products are exposed to vibration with the simultaneous supply of a drying agent, which is a mixture of heated air and ozone of a certain concentration.

2. In the course of experimental studies of energy parameters of the vibro-ozonation complex:

- it was established that with the increase in the temperature of the drying agent T, the consumed power N_1 by the heating electric elements increases practically proportionally;

- an increase in power consumption by the electric motor of the unbalanced shaft drive was found depending on the total loading volume of the drying chamber, which at an operating angular velocity of ω = 90 rad/s is: N_2 = 480 W at 75% load and N_2 = 450 W at 50% load;

- it can be concluded that with an increase in the frequency of rotation of the electric motor, the power consumed by it increases. In addition, at the maximum revolutions of the electric motor (n = 3000 rpm), the power consumed by it is N_3 = 0.115 kW at a speed of the drying agent of 3 m/s and a load of 50% of the full volume of the drying chamber and at a speed of the drying agent of 2.5 m/s with loading 75% of the full volume of the drying chamber;

- it was established that with an increase in the concentration of ozone N_{O3}, the power consumed by the electronic device for the synthesis of ozone N_4 increases, practically, in direct proportion.

3. Based on the obtained data, it was determined that the specific energy consumption per unit of finished products with a moisture content of 14% at an initial moisture content of 20% is:

- using classic technology with the supply of a drying agent at a temperature of 50 °C with a treatment duration of 240 min – 112.93 W·h/kg or 18.82 W·h/kg per 1% of evaporated moisture (406.54 kJ/kg or 67.75 kJ/kg per 1% of evaporated moisture);

- for the use of complex thermophysical influence with a treatment duration of 160 min – 91.01 W·h/kg or 15.16 W·h/kg per 1% of evaporated moisture (327.63 kJ/kg or 54.6 kJ/kg per 1% of evaporated moisture).

4. It was established that the energy consumption of the developed vibro-ozonation complex is most affected by the processing time t and the temperature of the drying agent T.

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