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EVALUATION OF THE ENERGY CHARACTERISTICS OF THE INFRARED DRYING PROCESS OF RAPESEED AND SOYBEANS WITH A VIBRATING WAVE DRIVER

Igor Palamarchuk[1], Vladyslav Palamarchuk[2], Marija Zheplinska[1]
[1]National University of Life and Environmental Sciences of Ukraine, Kyiv, Ukraine, [2]Vinnytsia Institute of Trade and Economics of State University of Trade and Economics, Vinnytsia, Ukraine

Abstract. *The developed thermal radiation dryer with a vibrating wave method of generating oscillations allows you to realize the positive features of the flow form of the processing organization, the level of influence of high thermal loads on the surface layer of products, the high rate of moisture removal deep into the product in conditions of ensuring its fluidized state. Under such conditions, energy-saving and uniform processing of the mass of technological loading is realized. The loosening of the mass of products under the influence of signs of variable loads to the reduction of internal friction and viscosity in the technological environment, which allows to maximize heat transfer coefficients. The implementation of the process of mixing loose particles of products during their transportation in the working area with a vibrating wave driver ensures constant renewal of the surface layer, layer-by-layer uniform heat treatment, which eliminates its overheating and sufficiently effective energy saturation under the action of high-energy infrared radiation. The vibration-wave method of creating a fluidized layer allows to soften the contact interaction with infrared rays in a certain way. In the developed vibro-wave thermoradiation dryer, vibration not only reduces the forces of internal friction during transportation, but also forms a dynamic wave to ensure the forced movement of material along a flexible load-carrying body under the conditions of continuous renewal of product layers during their mixing. Based on the results of the research, it was substantiated that the most effective were the speeds of product advancement in the range from 0.15 to 0.3 cm/s, the rational values of the power of infrared radiation were 400–500 W, and the specific loading of the conveyor belt was expedient to use up to 3.5 kg/m^2.*

Keywords: energy potential of infrared radiation, thermoradiation dryer, driving force, energy saturation of product mass, vibration wave driver, traveling wave

OCENA CHARAKTERYSTYKI ENERGETYCZNEJ PROCESU SUSZENIA PODCZERWIENIĄ NASION RZEPAKU I SOI PRZY UŻYCIU WIRNIKA WIBRACYJNEGO

Streszczenie. *Opracowana suszarka cieplna z metodą fali wibracyjnej generującej oscylacje pozwala uświadomić sobie pozytywne cechy kształtu przepływu organizacji przetwarzającej, poziom wpływu dużych obciążeń termicznych na wierzchnią warstwę produktów, wysoką szybkość usuwania wilgoci w głąb produktu w warunkach zapewniających jego stan upłynniony. W takich warunkach realizowane jest energooszczędne i równomierne przetwarzanie masy wsadu technologicznego. Rozluźnienie masy wyrobów pod wpływem oznak zmiennych obciążeń w celu zmniejszenia tarcia wewnętrznego i lepkości w środowisku technologicznym, co pozwala maksymalizować współczynniki przenikania ciepła. Realizacja procesu mieszania sypkich cząstek produktów podczas ich transportu w obszarze roboczym za pomocą wibratora falowego zapewnia ciągłą odnowę warstwy wierzchniej, równomierną obróbkę cieplną warstwa po warstwie, co eliminuje jej przegrzanie i wystarczająco efektywne nasycenie energią pod wpływem działanie wysokoenergetycznego promieniowania podczerwonego. Metoda wibracyjno-falowa tworzenia warstwy fluidalnej pozwala w pewien sposób złagodzić oddziaływanie kontaktowe z promieniami podczerwonymi. W opracowanej suszarce termoradiacyjnej wibracyjnej wibracje nie tylko zmniejszają siły tarcia wewnętrznego podczas transportu, ale także tworzą falę dynamiczną, która zapewnia wymuszony ruch materiału wzdłuż elastycznego korpusu nośnego w warunkach ciągłej wymiany warstw produktu podczas ich mieszania. Na podstawie wyników badań stwierdzono, że najskuteczniejsze były prędkości przesuwania produktu w zakresie od 0,15 do 0,3 cm/s, racjonalne wartości mocy promieniowania podczerwonego wynosiły 400–500 W, a właściwa celowe było obciążenie przenośnika taśmowego do 3,5 kg/m^2.*

Słowa kluczowe: potencjał energetyczny promieniowania podczerwonego, suszarka termoradiacyjna, siła napędowa, nasycenie energetyczne masy produktu, sterownik fali wibracyjnej, fala biegnąca

Introduction

The drying process is one of the most common in food production and the most complex among heat and mass exchange processes, which consists of successive stages of heat transfer to products through the boundary layer at the heat return stage; phase transformation at the stage of evaporation; transfer of moisture and heat throughout the material at the stage of heat and mass transfer; transfer of moisture and heat from the surface of the material to the surrounding environment through the boundary layer at the stage of heat exchange [25]. Therefore, the implementation of such a complex of actions with high energy efficiency is urgent. In this scientific work, it is proposed to ensure the minimization of energy consumption for the process by using infrared or thermal radiation drying as a factor of intensification, vibration and wave effects in product layers.

Oscillation of the conveyor belt during the drying process allows to create a running wave on the working surface, and the moving layer of the product is transformed into a fluidized one. A traveling wave creates an impulse for longitudinal movement. The pseudo-liquefied layer of products leads to a significant increase in the equilibrium positions of individual particles of the material, due to which the contact between them and the supporting surface is lost, the conditions of contact interaction of the energy carrier are significantly improved, intensifying the heat and mass exchange processes [3–5, 26].

When implementing infrared drying in during the heat exchange process, the radiant flow partially penetrates into the capillary-porous bodies to a depth of 0.1...2 mm and is almost completely absorbed due to a series of reflections from the capillary walls. The heat and mass transfer coefficient of this process is so high that, compared to the convective or conductive method, drying can be reduced by 30...100 times [15, 17]. However, complex problems remain in terms of the process: high thermal stresses of infrared radiation; in the design of the load-bearing body: during transportation, the product is stationary and pressed against the supporting surface; from a technical and economic point of view: relatively high energy consumption of thermal radiation drying.

Modern constructive solutions of thermal radiation dryers in recent years have made it possible to equalize the energy consumption during their operation with convective devices. In this scientific work, the energy efficiency of the infrared drying process is investigated when using a driver based on vibration and wave effects, which made it possible to significantly reduce the heat load on the product layers while maintaining the current form of processing organization. Thus, the main hypothesis of the work is that increasing the degree of freedom of product particles significantly increases the mobility of the entire product layer and leads to a constant renewal of contact surfaces with intense infrared radiation, reducing the thermal load on products to an acceptable level; at the same time, the drying speed increases, which indirectly reduces the energy consumption of the process.

1. Analysis of literary data and statement of the problem

Without knowledge of the patterns of influence of technological loading, it turned out to be impossible to calculate the machine under load and determine the necessary energy consumption during its operation. In the vibration field, the oscillating surface provides force pulses from the lower to the higher layers of the technological load. As a result of the action of frictional forces and irreversible deformation associated with energy dissipation, the vibration pulses as they are transmitted from one monolayer to another gradually decay depending on the properties of the technological environment and the magnitude of the force parameters of the vibration. At the same time, the farther from the source of vibration the loading monolayer is located, the smaller the amplitude of the periodic component of its movement [18, 19, 24].

It was established that the loading impact on the oscillating surface is far from instantaneous and its duration is equal to the cycle of the medium movement (up to 40%). When solving this problem, the load was approximated either by viscous supports, or by dry friction, or was presented in the form of "dry mass", or in the form of a combination of the specified parameters. In addition, experimental studies revealed a very high unevenness of the load from technological loading: in the area of free movement, the studied interaction forces are practically absent, in the area of collisions they exceed static loads many times over, and in the area of combined movement they become equal to the force of the weight of the loading mass. Dynamic loads in the system are formed depending on the law of motion of the technological environment of the machine itself. Therefore, as it was stated in works [1, 20, 21], the "attached mass" method, which is reduced only to the calculated increase in the mass of the working body of the vibrating machine, does not at all reflect the essence of the phenomena of the movement of bodies in the vibration field. The inadmissibility of increasing the oscillating mass of the vibrating machine due to the addition of loading mass was noted by the authors [4] due to the fact that the law of its motion differs from the oscillating mode of the machine's executive bodies.

In works [7, 9, 12, 22], loading was modeled by a material particle, the mass of which instantly joins the mass of the load-carrying body in the area of simultaneous movement. A method of calculating the impact of loading during extended co-impact with a vibrating surface was proposed, in which the "attached mass" was determined taking into account the mode of operation of the vibrating machine. In addition, a logical system was developed that carried out the transfer of the solution of this problem to various systems of equations that describe the state of the "vibrator-loading" system in each of its possible positions.

In-depth experimental studies of the "load-vibrator-engine" system during vibration transportation were carried out by the authors [2, 6, 8, 10]. Technological systems that combine the processes of continuous transportation of products and their heat and mass exchange processing, in particular, drying, are characterized by the complexity of the constructive implementation of their elements due to the need to use special transport devices, which often negates the advantages of the current processing mode. When ensuring the energy efficiency of drying, it is necessary to resolve the process conflict: the use of modern technologies and equipment for intensifying the heat exchange process and leveling the negative thermodynamic impact on product quality. Therefore, the development of a technical system combining a vibrating process driver and a flexible load-carrying belt has wide prospects and relevance when used in modern technologies of processing and food industries.

2. The purpose and objectives of the research

The purpose of the conducted research is the justification of energy-efficient modes of implementation of thermoradiative drying with a vibrating wave driver of the process by means of theoretical and experimental determination of the driving force, parameters of the energy potential of the investigated process. To fulfill the set goal, the following tasks were planned:

- preparation of an experimental model of a thermal radiation dryer with vibration-wave transportation of products and the formation of a measuring base for conducting research;
- determination of the driving force and compilation of the power balance of the studied drying process;
- assessment of the energy saturation of infrared radiation when the main technological parameters of the heat-mass exchange oscillating system are changed;
- justification of energy-efficient modes of implementation of infrared drying with vibration wave transportation in conditions of a fluidized bed of products.

3. Materials and methods

To study the influence of energy parameters during infrared irradiation on the efficiency of moisture removal from the product, an experimental setup was created, the scheme of which is given in the authors' article [14].

When conducting experimental studies, an electromagnetic field with a dosed power of 100, 200, and 300 W was created using one, two, or three emitter units. The power of the emitters was adjusted by changing the current strength with the help of a laboratory autotransformer AOSN-20-220-75. The vibration frequency of the vibration wave driver of the infrared dryer under study was measured using a UNI-T UT372 frequency meter. The evaluation of the power and energy parameters of the investigated installation made it possible to determine the energy consumption of the drive and build the power balance of the process.

Amplitude-frequency, power and specific energy characteristics were determined using German Robotron equipment. To do this, we used the assessment of the kinematic parameters of vibration, in particular, the components along the coordinate axes of movement, vibration velocity, and vibration acceleration. The main energy parameters of the investigated thermoradiation drying process include the work of forcing forces or moments and internal resistance forces of the oscillating system; the energy of the electromagnetic field during radiation, which was determined by the power consumption of the emitter units; power to drive the vibrator.

4. Results and discussion

The work of external forces is created by the vibration exciter and is spent on overcoming the resistance forces of the system and ensuring the oscillating movement of the executive bodies of the vibrating technological machine with the specified parameters. The internal resistance forces of the oscillating system are reactive and dissipative resistance forces.

The work of the reactive resistance forces is the work of the inertial forces of the moving mass and the forces of deformation of the elastic elements of the oscillating system. In other words, the reactive resistance energy of the system consists of the kinetic energy of the moving mass and the potential energy of the deformation of the elastic elements. In the algebraic expression, each of the considered components has different signs, which constantly change according to the oscillatory motion of the elements of the vibration system [11, 23]. Then, in the case when the calculation is carried out for an integer number of complete oscillations, both works are excluded from the total energy balance of the system. The mass of the working body of the machine, which perceives oscillating motion and its elastic connections, determine the ability of the system to accumulate energy, which is transferred, in the future, from one form to another. The level of energy accumulation and the ratio between the kinetic and potential energy of the reactive elements are determined by the vertical component of the forcing force. Inflow of energy from an external source to overcome reactive resistance is not required if the amplitude values of the kinetic and potential energies, respectively, of the moving mass and elastic elements are equal.

The work of dissipative resistance forces is the work of friction forces, which leads to the dissipation of energy and its transformation into heat. The energy dissipation of the oscillating system contains hysteresis energy costs during spring deformation; the energy dissipated in the dampers of the working bodies and support nodes of the vibrating machine; energy consumed in the working environment of the vibrating technological machine due to dry and narrow friction; energy consumption for friction in the joints of various connections, for overcoming air resistance, and others.

In addition, part of the energy supplied from an external source is spent, as a rule, in various intermediate gears, connecting couplings, in the electric motor itself and in other devices of the vibrating machine. Energy consumption in mechanical transmissions depends on the structural scheme of the vibrating machine and is determined as a result of special kinematic calculations [13, 16, 23].

The energy consumption in the electric motor consists of the consumption of the stator and rotor of the electric machine. The energy in the stator is spent on remagnetization, on eddy current in the magnetic conductor of the stator, on heating of the stator winding by the current. In the rotor, energy is consumed during heating of the winding and in the magnetic circuit. The latter are practically zero due to the small value of the frequency of flows in the electric circuit of the rotor. Energy costs for remagnetization, eddy currents in the magnetic field are constant for this type of electric motor and do not depend on the load on the motor shaft. Energy consumption for heating the stator and rotor windings depends on the amount of current, which is determined by the useful power required to drive the vibrating machine. At the same time, the power balance equation is presented in the form:

$$N_k = N_0 - (N_{vs} + N_{vr} + N_m + N_{ad}), \tag{1}$$

where N_k is useful power per drive; N_0 – power of energy supplied from the power grid; N_{vs} and N_{vr} – power consumption in the stator and rotor; $N_{ad} = 0.005N_0$ – additional power consumption; N_m is mechanical power consumption.

Thus, among the main energy parameters of vibration, the components of the energy balance, the work of internal and external forces of the oscillating system, specific energy characteristics related to the unit of oscillating mass of the vibration drive and to the unit of product mass can be distinguished.

The power supplied from the power grid to the electric motor is quite conveniently determined by the amount of energy needed to ensure technological movement. The latter is understood as the implementation by the executive bodies of the installation of a given oscillatory mode, which ensures both the advancement of the product mass along the working area to unloading, and the creation of the necessary thermal effect by infrared radiation. Therefore, the power consumption during the implementation of infrared drying in a vibrating weighted layer of products is

$$N_0 = N_{on} + N_{np}, \tag{2}$$

where N_{on} – power consumption to ensure processing of products by infrared irradiation with the required intensity of processing; N_{np} – power consumption of the drive, i.e. to implement the operation of vibration exciters with the necessary amplitude-frequency characteristics, which can be defined as:

$$N_{np} = \eta^{-1}\left(N_{F_{max}} + N_t\right), \tag{3}$$

where η is the transmission efficiency ratio; N_t – power consumption for friction in support nodes; $N_{F_{max}}$ – the maximum power developed by the forcing force.

The indicated value of the forcing force is the driving force of the process of vibration action, which can be determined from the dependence:

$$N_{F_{max}} = m_d \cdot a_x \cdot v_x = m_d \cdot A\omega^2 \cdot \boldsymbol{v_x}, \tag{4}$$

where m_d is the mass of the active oscillating mass, which is the unbalance mass for the vibration drive under study; A, ω – amplitude and frequency of oscillations generated by the vibrator, respectively; a_x and $\boldsymbol{v}_x$ – respectively, the acceleration and speed of movement of the product mass flow along the horizontal axis x, which arise as a result of the generated oscillatory motion; therefore, these parameters are called vibration acceleration and vibration speed.

When using the developed installation, the vibration exciters are mounted in two support rollers, which generate low-frequency oscillations with the corresponding amplitude-frequency characteristics. Therefore, it is important to synchronize their work in such a way as to create a movement of the product flow at a speed sufficient to achieve the desired level of moisture content. In general, the value of the power of the coercive force F_{max} is:

$$N_F = m_d \cdot v_{mpx} = m_d\left(a_{x_1} + a_{x_2}\right) \cdot v_{mpx} = \\ = m_d\left(A_{x_1} \cdot \omega_1^2 + A_{x_2} \cdot \omega_2^2\right) \cdot v_{mpx}, \tag{5}$$

where is a_{x_1}that a_{x_2}– vibration acceleration provided to the belt from the vibration exciters of the dryer; $A_{x_1}$and A_{x_2}– amplitudes of oscillations generated by the indicated vibration drives, ω_1 and ω_2 are the angular velocities of the drive shafts of the corresponding vibration exciters.

These parameters were determined from the results of experimental studies during operation of the developed vibro-conveyor infrared dryer under conditions of simultaneous operation of two vibration exciters. Thus, stable transportation of products by a vibrating conveyor, while ensuring the necessary productivity and quality of processing, was observed with the following ratios of the amplitude-frequency characteristics of the drives:

$$A_{x_2} = 1.68 \cdot A_{x_1};\ \omega_2 = 1.22 \cdot \omega_1. \tag{6}$$

The study of the energy characteristics for the characteristic positions of the unbalanced elements made it possible to obtain graphical dependences of the vibration parameters in Fig. 1 and 2. The design of vibration exciters in the developed thermal radiation dryer is characterized by the simplicity of modeling the process of generating oscillations when the position of a pair of imbalances is changed relative to the vertical axis of the opposite pair, which allows realizing force, moment and combined imbalances of the studied oscillating system (Fig. 1).

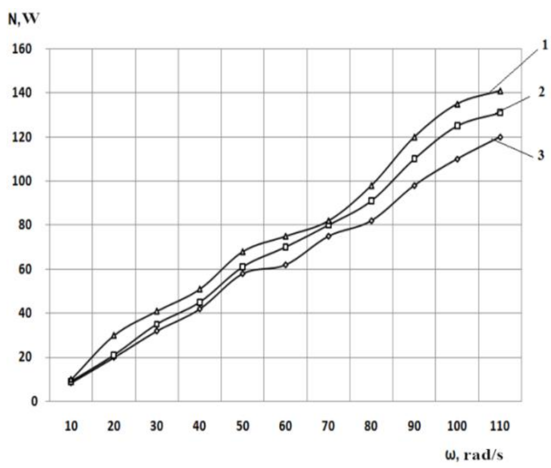

Fig. 1. The energy characteristic of the machine under study depending on the angular speed of rotation of the drive shaft for the implementation of the following modes of generation of low-frequency oscillations: 1 – with combined unbalance; 2 – with momentary imbalance; 3 – with power imbalance

For the nominal mode of mechanical vibration excitation of the technological oscillating system, which in the studied system is 90–110 rad/s [17,18,19], an increase in energy consumption up to 20% was observed from power to combined imbalance of vibration exciters. However, in the case of combined imbalance, there is an increase in the change in the equilibrium positions in the longitudinal direction, which allows to increase the speed of the forward movement of the product mass along the working zone by 1.5–1.6 times. This effect is due to the increase in the driving force of the transportation process due to both the driving force and the moment.

When mounting one pair *of* imbalances at different angles of location of inertial elements relative to each other, the generated inertial force changes from zero to a doubled value (Fig. 4). At the same time, the driving force of the process increases accordingly. In this study, the parameter of the intensity of oscillatory motion, which can be determined through the following products [20], was used as an evaluation criterion:

$$N_m = A^2 \cdot \omega^3 = a \cdot \boldsymbol{v} = N/m \qquad (7)$$

where m is the mass of oscillating parts of the vibration drive, which for power vibration excitation is 1.5…2.5 times greater than according to kinematic or combined schemes [21].

This characteristic determines the specific power consumption, which makes it possible to attribute this indicator to the group of techno-economic and energy evaluation parameters. For the angle of dilution of imbalances 0^0, the forcing force is doubled [22]. This mode of vibration excitation is characterized by an earlier resonant mode; for frequencies of 100…110 rad/s, the intensity of the oscillatory motion increases by 10% compared to the mode of half the forcing force for the angle of dilution of imbalances of 90^0; and for a frequency of 135 rad/s, the increase in intensity reaches 50% (Fig. 2).

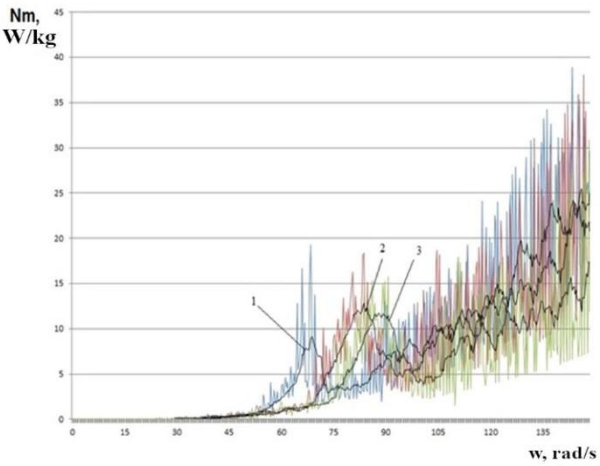

Fig. 2. The intensity of the oscillating motion of the machine under study depending on the angular speed of rotation of the drive shaft and the angle of dilution of imbalances: 1 – at 0 degrees; 2 – at 45 degrees; 3 – at 90 degrees

Further studies of the energy characteristics of the infrared drying process with a vibrating wave driver concerned the influence of the intensity of irradiation on it. As an assessment criterion, the actual power of the electromagnetic effect of irradiation, as well as the number of successively located emitter blocks (Figs. 3 – 6) were used.

As can be seen from figure 3, with an increase in the speed of product advancement by 38% and a decrease in the energy saturation of products with radiant energy by 1.5 times, the drying speed of soybeans increases by almost 25% when using 2 and 3 radiator modules. When using one panel of emitters, the drying speed practically did not change under the specified technological conditions.

When the speed of product advancement along the processing zone was reduced by 4 times, while the energy potential from infrared radiation was constant, the drying speed of soybeans decreased by only 25% when using three units of emitters. Under the conditions of operation of two panels, a 50% increase in the speed of moisture removal was observed, and when using one panel, the speed increased by almost 1.5 times (Fig. 4) under the presented technological conditions.

When the energy saturation of the mass of rapeseed by infrared irradiation increased by 3 times at the same speed of movement of products and load on the belt (Fig. 5), an increase in the drying speed was observed under the action of three panels of emitters by 5.3 times, with two panels – by 6 times, and when using of one block – 5.52 times. That is, under the presented technological parameters, the energy saturation of the infrared field practically does not affect the processing result.

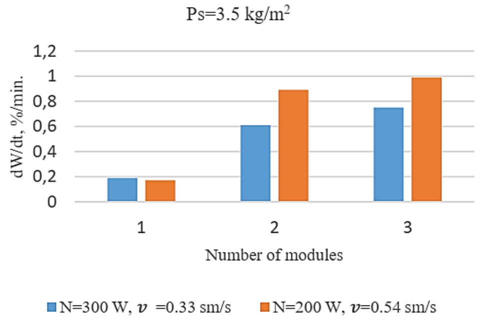

Fig. 3. Changing in the speed of transportation of products and the power of irradiation in the process of infrared drying of soybeans

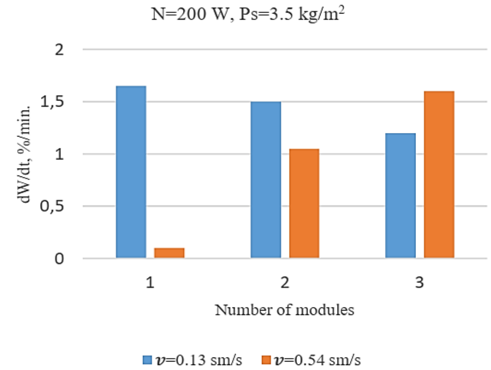

Fig. 4. Changing in the speed of transportation of products in the process of infrared drying of soybeans

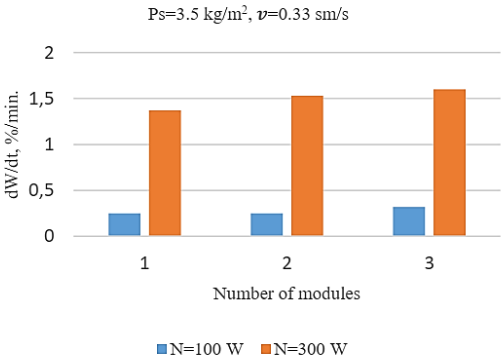

Fig. 5. Changing the load of products on the conveyor belt and the power of irradiation in the process of infrared drying of rapeseed

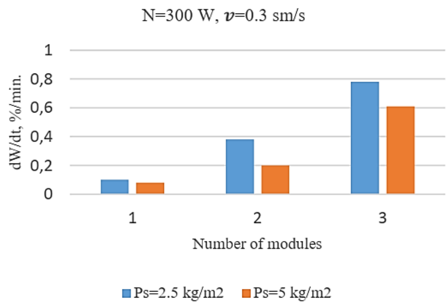

Fig. 6. Changing the product load on the conveyor belt during the infrared drying of rapeseed

With a 2-fold increase in the specific load of the products on the surface of the tape, unchanged speed of product advancement and infrared radiation energy (Fig. 6), a decrease in the rate of moisture removal of rapeseed was observed when using three blocks of emitters by 25%, two blocks by 20%, one block – practically has not changed.

According to the results of the presented graphical studies (Fig. 3 – 6), fairly effective parameters of the process were observed: the speed of product transportation in the range from 0.15 to 0.3 cm/s, the power of infrared emitters 400…500 W. The typical loading of the conveyor belt should not be set higher than 3.5 kg/m^2, because this may lead to a decrease in the quality of processing due to a decrease in the permeability of infrared rays in the product layer at relatively high speeds of the belt movement. Experimental studies have established the expediency of using three successively located blocks of infrared emitters. This made it possible to increase the amount of moisture removed and reduce the power of the emitters by 40% (from 500 to 300 W).

5. Conclusions

1. An increase in the mass of the oscillating parts of the drive leads to a corresponding increase in the intensity of energy saturation of the product mass, but also an increase in energy consumption by 20%. The developed method makes it possible to increase the intensification of heat and mass exchange by using a fluidized bed of products; the use of a vibration wave engine allows to potentially increase the productivity of processing due to the implementation of the current scheme of production organization.
2. Increasing the energy potential of infrared radiation by 3 times made it possible to increase the drying speed of products by 5–6 times.
3. According to the results of experimental studies, the most effective parameters of the process were: the speed of product transportation in the range from 0.15 to 0.3 cm/s, the power of infrared emitters 400 – 500 W. An increase in the specific load of soybeans and rapeseed to 3.5 kg/m^2 leads to an increase in moisture output due to the rational penetration of infrared rays into the entire layer of the product.

References

[1] Afzal T.M., Abe T., Hikida Y.: Energy and quality aspects during combined FIR convection drying of barley. Food Eng. 42, 1999, 177–182.
[2] Bahlul N. et al.: Coupling of Microwave Radiations to Convective Drying for Improving Fruit Quality. 21st International Drying Symposium, 2018, 699.
[3] Bandura V., Zozuliak I., Palamarchuk V.: Description of heat exchange in the similarity theory of vibrating drying process of sunflower. Ukrainian Journal of Food Science 2(2), 2014, 305–311.
[4] Bandura V., Palamarchuk V.: Development of constructive and technological measures to increase the efficiency of infrared drying of energy-rich vegetable raw materials. IV International Scientific and Practical Conference "Land of Ukraine – the potential of economic and environmental security of the state", Vinnytsia, 2014, 24–27.
[5] Bandura V., Tsurkan O., Palamarchuk V.: Experimental study of the technological parameters of the process of infrared drying of the technological parameters of the process of infrared drying of the moving layer of the raw material of oilseed crops. MOTROL. Commission of Motorization and Energetics in Agriculture 17(4), 2015, 211–214.
[6] Bezbakh, I., Bakhmutyan, N.: Research on the process of drying fruits and berries in a suspended layer. Scientific works of ONAKHT, Odesa 28(2), 2006, 112–116.
[7] Burdo O. H.: Energy monitoring of food production. Polygraph, Odessa 2008.
[8] Derevenko V.: The main technological regularities of heat treatment of oily material for oil extraction. The Russian School of Problems of Science and Technology dedicated to the 80th anniversary of the birth of Academician V. P. Makeeva, Miass, 2004, 144–146.
[9] Didur V., Tkachenkom O.: Justification of the modes of drying sunflower seeds of higher reproductions in a fluidized bed. Pr. TDATA 25, 2005.
[10] Drukovany M. et al.: Improvement of thermal technology in the production of oil and biodiesel fuel: monograph. Vinnytsia 2014.
[11] Jayas D. S., Ghosh P. K.: Preserving quality during grain drying and techniques for measuring grain quality. Department of Biosystems Engineering, E2-376 Engineering and Information Technology Complex, University of Manitoba 2006, 969–980.
[12] Kotov B. I., Kyfyak V. V.: Identification of dynamic modes of heating and drying of grain products by IR radiation. Scientific Bulletin of the National University of Bioresources and Nature Management of Ukraine. Series: Technology and energy of agricultural industry 194(2), 2014, 165–170.
[13] Palamarchuk I. et al.: Physical-mathematical modeling of the process of infrared drying of rape with vibration transport of products. Mechatronic Systems 1, 2021, 243–253 [https://doi.org/10.1201/9781003224136-21].
[14] Palamarchuk I. et al.: An analysis of power and energy parameters of the conveyor infrared dryer of oil-containing raw materials. Informatyka, Automatyka, Pomiary w Gospodarce i Ochronie Srodowiska – IAPGOS 13(2), 2023, 10–14 [https://doi.org/10.35784/iapgos.3487].
[15] Palamarchuk I., Bandura V., Palamarchuk V.: Justification of the structural and technological scheme of the conveyor vibrating dryer. Vibrations in engineering and technologies 2(66), 2012, 116–125.
[16] Palamarchuk, I., Bandura, V., Palamarchuk, V.: Analysis of the dynamics of a vibrating conveyor technological system with kinematic combined vibration excitation. MOTROL. Commission of Motorization and Energetics in Agriculture 4(15), 2013, 314–323.
[17] Palamarchuk I., Bandura V., Palamarchuk V.: Vibrating conveyor dryer with infrared emitters: patent of Ukraine No. 87767; statement 28.02.2013; published 25.02.2014, Bull. No. 4, 4.
[18] Palamarchuk I., Bandura V., Palamarchuk V.: Selection of the type of mechanical drive for a conveyor vibrating dryer with flexible working and transporting bodies. Materials of the IV international scientific and practical conference "Innovative energy technologies", Odesa, 2016, 27–30.
[19] Palamarchuk I., Tsurkan O., Palamarchuk V.: Justification of the structural and technological scheme of the infrared vibrating conveyor dryer for post-harvest processing of loose agricultural products. Collection of scientific works of the Vinnytsia National Agrarian University. Series: Technical sciences 1(89), 2015, 117–123.
[20] Snezhkin Yu. F.: Ways of intensification of drying processes. Industrial heat engineering 31(7), 2009, 89–90.
[21] Sorochinsky V. F.: Efficiency of grain drying on grain dryers of various types. Bread products 3(4), 2009, 42–43.
[22] Sorochinsky V. F.: Estimation of the homogeneity of the fluidized bed of grain by changes in the local heat flux density on the vertical surface of the heat exchange. SETT-2002, 2, 72–75.
[23] Vasyliv V. et al.: Method of Electrohydraulic Activation of Water-Lime Suspension in Sugar Production. Tonkonogyi V. et al. (eds): Advanced Manufacturing Processes III. InterPartner 2021. 2022.
[24] Wei Q. et al.: Effects of Different Combined Drying Methods on Drying Uniformity and Quality of Dried Taro Slices. Drying Technology 37(3), 2019, 322–330 [https://doi.org/10.1080/07373937.2018.1445639].
[25] Zheplinska M., Mushtruk M., Salavor O.: Cavitational Impact on Electrical Conductivity in the Beet Processing Industry. Tonkonogyi V. et al. (eds) Advanced Manufacturing Processes II. InterPartner 2020. 2021.
[26] Zheplinska M. et al.: Exploration of drying process of beets. Journal of Hygienic Engineering and Design 42, 2023, 315–320.

D.Sc. Igor Palamarchuk
e-mail: vibroprocessing@gmail.com

Doctor of Technical Sciences, professor, National University of Life and Environmental Sciences of Ukraine. Department Processes and Equipment of Agricultural Production Processing, Kyiv, Ukraine.
Research Interests: design and development of mechanical and heat-mass exchange processes and equipment of processing and food industries with vibromechanical intensification of raw material processing.

http://orcid.org/0000-0002-0441-6586

Ph.D. Vladyslav Palamarchuk
e-mail: kupc1989@gmail.com

Canditate of Technical Sciences, Vinnytsia Institute of Trade and Economics of State University of Trade and Economics. Department of Commodity Studies, Expertise and Trade Entrepreneurship, Vinnitsia, Ukraine.
Research Interests: research on issues of intensification of the process of drying oily raw materials.

http://orcid.org/0000-0002-7478-9521

Ph.D. Marija Zheplinska
e-mail: jeplinska@ukr.net

Canditate of Technical Sciences, associate professor, National University of Life and Environmental Sciencesof Ukraine. Department Processes and Equipmentof Agricultural Production Processing, Kyiv, Ukraine.
Research Interests: technological and dynamic processes of equipment of food industries.

https://orcid.org/0000-0002-7286-3003