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ECHNOLOGY AND TECHNIQUE OF GRAIN DRYING

ТЕХНОЛОГІЯ І ТЕХНІКА СУШІННЯ ЗЕРНА

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Abstract. *The article provides a detailed review of technologies and techniques of grain drying. Attention is paid to the transformation of the agrarian industry during the war.*

One of the main problems of providing quality grain is its storage. Along with promising methods of grain preparation for storage, special attention is paid to the method of infrared irradiation as one of the physical methods of food processing. With the use of infrared radiation, the duration of heat treatment is significantly reduced due to the lack of thermal resistance of the boundary layer of the product to the radiant flux, the energy of which is directly absorbed by the surface of the raw material particles. At the same time, infrared radiation is actively absorbed by water contained in the product, but is not absorbed by the fabric of the product that is dried or heat treated.

Key words: *drying, grain, infrared radiation, humidity, power, soybean, rapeseed.*

Introduction.

Drying of grain, as a technological component, has long been known as a process that prevents spoilage of grain that has not been processed and it was necessary to bring it to a stable state for long-term storage.

The war in 2022 also made its adjustments to the grain storage process in Ukraine. This year, the Agrotransformation 2022 project was launched. In the conditions of waiting for the opening of ports, overcrowded elevators, or the risk of damage to elevators during massive shelling, high storage costs, and the establishment of favorable prices for farmers for grain and oilseeds, polymer sleeves as a means of storing grain have become increasingly necessary and popular. Therefore, along with the classical methods of grain preparation for storage, new approaches and technologies are emerging.

But, despite the universality of new methods, the process of stabilization of moisture in grain, necessary for storage of grain crops, remains problematic. This is inextricably linked to the need for continuous improvement of the technology of basic operations of post-harvest grain processing and, above all, drying, since it is this final operation that determines the quality of preservation of the harvested crop.

Analysis of recent research and publications. Freshly harvested grain (grain heap from under combine harvesters) is a colloidal capillary-porous body consisting of dry matter, water and air. In grain, as in any living organism, there are various life processes, including respiration. Important factors determining the intensity of biological and biochemical processes in grain are its temperature and humidity. At higher humidity and temperature, the respiration process is enhanced, and as a result, the intensity of heat generation and mass loss increases [5,10,15]. The resulting "sources" of self-heating promote the growth of microorganisms, harmful insects, reduce the food quality of grain and cause seed spoilage.

But already at a grain moisture content of 14% and below, the grains are in a state of anabiosis, that is, their vital activity and respiration become minimal. Thus, the main purpose of drying is to remove excess moisture from the grain to increase its stability during further storage.

The main requirements for the drying process are to preserve and improve the technological quality of grain. During drying, grain properties should be fully preserved and, if possible, improved in accordance with its purpose: color, shape, appearance, viability, feed and food quality.

Reduction of grain moisture creates unfavorable conditions for the development and existence of pests. High temperatures applied with appropriate heating exposure are an effective measure for the destruction of pests.

Compared to other methods of grain disinfection (chemical, mechanical, etc.), the thermal method has significant advantages.

Thus, drying, which allows to store and process hundreds of thousands of tons of harvested grain annually, to improve its quality, is of great national economic importance. This determines the goal and objectives of further improvement of technology and technical means for drying grain.

Modern grain drying technology is based mainly on the method of thermal drying, when moisture is removed from the grain to its surface, and evaporates from the surface into the environment. That is, the method is based on the principle of using heat to convert water from liquid to gaseous state, which is associated with significant heat consumption.

The main parameters of the drying mode are the temperature and speed of the drying agent, the temperature (edge) heating of the grain in the drying chamber, the thickness of the grain layer in the direction of movement of the drying agent and the exposure of the grain heating (and cooling) process.

We will analyze the existing (recommended) drying modes, using modern technologies and approaches along with fundamental works [1-31].

For shaft grain dryers, single-stage and differentiated modes of drying wheat grain are provided, under which the temperature of the drying agent is set from 90 to 160°C (depending on moisture, and in differentiated modes - depending on fiber), which increases stepwise from the direction of grain movement in the shaft. As a result of the adopted ascending change in the temperature of the drying agent, the grain is slowly heated in the shaft, and its temperature reaches the limit value only at the end of the drying zone. Ascending and differential modes were substantiated by the need for gradual heating of grain to exclude "hardening" of grain. The recommended modes based on the dependence of biological changes during grain heating on humidity and time of thermal exposure were worked out. In the proposed modes, it was assumed to increase the heating of grain in the process of reducing its moisture content in accordance with the limit of "conditionally safe" temperatures. Thus, in the mode after the grain reaches a temperature of 50° C, a further gradual increase in its temperature to 70° C allows to increase the moisture yield of grain by 55 ... 79% [16]. It should be noted that from a thermodynamic point of view, increasing the initial temperature is always advisable, since it increases the thermal efficiency of the dryer [4, 9].

To increase the efficiency and productivity of shaft dryers, descending progressive modes have been developed, under which the grain is heated to 35...400C at the end of 0.25 height of the drying zone of the shaft. A drying agent with a temperature of 170...190°C is supplied to this heating zone. It is established that after rapid heating of the grain, the change in its temperature in accordance with the edge temperature is achieved by reducing the heat flux, which for downward modes is carried out by reducing the drying temperature during the process to 120°C. At the same time, the grain does not "harden". But the increase in grain temperature with a decrease in its moisture content is quite complicated by the imperfection of the design of grain dryer shafts.

Reducing the amount of heat supplied to the grain in the direction of its movement can also be achieved by changing the speed of the drying agent and the thickness of the grain layer along the height of the shaft. The downward distribution of heat allows to reduce the exposure of grain heating and more fully meets the need for heat to remove moisture due to a decrease in the intensity of drying by the height of the shaft.

For shaft grain dryers, a pulse drying method has been developed, which is based on the alternation of heating and cooling of grain (or grain storing). This made it possible to increase the temperature of the drying agent to 150...210°C. The pulse method significantly intensifies drying and increases the thermal efficiency of the grain dryer.

With the introduction of the method of determining the quality criterion for drying grain (both seed and food) by germination, the introduction of "reduced" and softened drying modes began to prevent losses in grain quality. This led to a decrease in the productivity of grain dryers by 20% [19] and an increase in specific energy consumption.

From the above review it can be concluded that the main technological measures to improve the efficiency of grain drying are to increase the temperature of the drying agent and the time of grain residence in the shaft. The latter has a negative impact on productivity. In this case, the grain is heated to the "edge" temperature only after passing most of the drying zone of the shaft.

Based on experimental data on the significant influence of the material temperature on the intensity of its drying, it was determined that a radical measure to further intensify the drying process in shaft dryers is preheating, and the technical implementation of such a technique can be the development of such modes when the grain temperature reaches its maximum value at maximum speed and maintains it until the end of the dehydration process.

In studies [17, 22], a significant step dependence of the coefficient of moisture diffusion in grain on the heating temperature was obtained:

$$a_m = a_{mo}\left(\frac{T}{293}\right)^n, \qquad (1)$$

where T - is the grain temperature;

a_{mo} - diffusion coefficient without heating;

n = 8...18 (depending on humidity).

Studies [15,22] have shown that preheating of grain in the "fast" mode allows to reduce specific energy consumption for drying by almost 2 times; at the same time, heat consumption for preheating increases by 60%. When the heating temperature is increased to 120°C, energy saving is 20%.

It is proved in [19, 24] that a progressive direction in the development of grain drying in the near future should be considered the transition from traditional shaft grain dryers to high-performance units with intensive heating of wet (raw) grain, followed by drying in isothermal mode with partial grain recirculation. Recycling of such modes will increase productivity by 25...30%, reduce fuel consumption by 10% and electricity by 10...15%.

It is shown in [29, 31] that, for any method of convective drying, grain stacking is one of the progressive methods of energy saving during grain drying; moreover, the influence of stacking on reducing heat and energy costs is higher, the lower the moisture-release ability of grain.

Different variants of the grain drying process at step, "progressive" and high-speed modes have found a constructive design, which is associated with the reconstruction and modernization of shaft grain dryers.

Research results.

In the world practice of grain drying different ways of utilization of the spent drying agent are used.

Some foreign companies ("Behlen", USA) produce grain dryers, in which the waste heat carrier is used for preheating of grain; in this case it is possible to utilize up to 10% of all heat consumed, but the possibility of condensation of moisture in the grain, which must be evaporated again in the future, is not excluded. Condensation can be prevented by applying preheating of grain. The most common method of reducing the energy intensity of grain dryers is partial recycling of the coolant through its reuse. The effect of heat saving according to generalized data is up to 300 kcal/kg. The principle of recirculation is used by grain dryers of American companies "Berico", "Campbell", "Blount", "Blaine", French "Love", "Cominor". These are multi-stage (multi-storey) dryers operating in "increasing" temperature regimes: cold air entering the dryer is heated in the first zone, then fed to a special heat generator to increase its temperature to 70...90°C, after which the drying agent enters the third zone, and then again to the heat generator, from which it enters the first zone. This makes it possible to return 30...40% of air to the cycle, which saves 10% of heat.

It is widely practiced to connect dryers with almost complete return of heated air and classical dryers in series. The company "Cecil" offered a dryer with a "saving unit", which is a dryer with almost 80% return of the drying agent, and a utilizer of a classic dryer.

Well-known dryers of "Law" company (France) work with recycling of drying agent.

There are several options for using the spent drying agent:

- use as a heat carrier for heating fresh air in different types of utilization plants;
- recirculation of part of the exhaust air (mixing with fresh air or with combustion products and air).

The second method is much simpler and more economical, but leads to an increase in drying time and a decrease in dryer productivity.

Abroad (France, USA, Poland) there is a wide variety of technical solutions to this problem: with the help of heat recycling (company "Law") and reuse of the exhaust air at the bottom of the dryer with a temperature of 50 ... 60° C, which is fed to the upper part of the shaft, or to the furnace.

Depending on the method of using the secondary heat and the design of the dryer, it is possible to reduce energy consumption from 1419 to 1257 kcal per kg of evaporated moisture.

Thus, the energy saving of 419 kJ/kg of moisture gives the method of double passage of the drying agent through the grain layer. Fresh coolant with a temperature of 120°C is supplied to the lower zone, and the spent coolant in the lower zone is slightly saturated with a temperature of 60...65°C is supplied to the upper zone for drying grain.

More economical is the method of drying grain in two zones with two furnaces. The furnace of the upper zone additionally heats the exhaust air in the lower air zone (up to 50°C), and after passing the layer of wet grain, the air is saturated, its temperature drops to 45...50°C. This method allows to reduce fuel consumption by 25% and bring energy consumption to 3352...3562 kJ/kg of moisture. A similar effect can be achieved by reusing the heated slightly saturated air in the lower part of the dryer, which is sent to the furnace with a temperature of 60...70°C, or mixing it with the heated air coming out of the furnace heated to 110°C. Fuel saving in this case is 20%.

According to the company "Cecil" (France), the inclusion of additional "economy units" in two-storey dryers, which can completely return warm air, will bring fuel consumption to 2807...2891 kJ/kg of moisture (for corn at a moisture content reduction from 35 to 15%). The F1-43M-50 dryer requires 4034 kJ/kg of moisture when the moisture content of wheat grain decreases from 20 to 14%. Thus, the sequential combination of a dryer with almost complete air return and a classical dryer when using the "economy unit" will allow to achieve the minimum specific energy consumption.

In the USA, the use of shaft dryers with recirculation of the spent drying agent and cooling air has recently become widespread. According to companies, such dryers save 50% of fuel. There are also dryers with parallel flows of drying agent, which moves from top to bottom in the direct flow with the grain, and cooling air, which moves in the counterflow with the grain.

In the «Mand W 450p» shaft direct-flow dryer, the drying process is carried out in three stages. At the first stage, part of the drying agent is used to preheat the grain. In the next stage, the grain moves downwards in a direct flow with the drying agent. At the third stage, cooled air passes through the dry heated grain, taking away some of the heat. All the cooling air and about 60% of the spent drying agent circulates between the fan and the combustion chamber. According to the manufacturers, fuel consumption saving reaches 35%.

In the grain dryer of the company «Bentley» (England) atmospheric air after cooling the grain is fed to the mixing chamber of the furnace, where it is mixed with combustion products and then fed to the drying zone.

In the grain dryer of «Svenska Flaktfabriken» (Sweden) atmospheric air from the grain cooling chamber is supplied to the steam heater of the second drying zone. At the exit from the second zone, the exhaust air is heated again and sent to the first zone of the dryer.

The well-known «Blant» dryers are equipped with a system of partial recirculation of the exhaust coolant and all the exhaust air in the grain cooler (CFR 10-60A dryer).

In the CFR 10-60A dryer, in addition to partial recirculation of coolant and air, there is also partial recirculation of grain and preheating of grain.

For rice drying, this company produces the SSR grain dryer, which uses preheating of grain conductively due to contact heat exchange by the drying agent exhausted in the lower zone with its intermediate heating. After heating, the grain is fed to the resting zone and then to the second drying zone, where it is treated with a fresh drying agent. After the cooling zone, the grain is again subjected to storing.

To reduce fuel consumption, «Omnium» (France) has improved the dryers. In the first drying zone, the thickness of the grain layer is reduced, which is processed by fresh coolant with a maximum temperature of 160°C, the temperature of the coolant is reduced in the course of grain movement to 110°C. The lower drying zone provides for the return of the spent coolant for recirculation. The air from the cooler is also reused.

"Law" company also offers dryers with recirculation of coolant and air cooling.

Dryers of SO.CO. company (France) belong to energy-saving equipment. Dryers are equipped with a system of recirculation and regeneration of coolants and air. In addition, they carry out heating (intermediate) of the coolant used in the lower zone.

The company "Flukt" (Finland) produces grain dryers, which contain drying, storing and cooling zones with multiple use of coolants, which allows to achieve heat consumption of 1200-1850 kcal per kg of moisture.

The "Behlen" dryer, applying the principle of reusable heat, becomes less efficient and more difficult to implement, as it requires additional heaters to heat them along the way.

The use of heat pumps for heating the drying agent instead of traditional installations (furnaces for burning liquid and gas fuels) can significantly improve the quality of the product, eliminate air pollution and utilize low-potential energy of thermal emissions from dryers. In addition, heat pumps make it possible to carry out heating and cooling of different process flows in one installation.

Air heating in the condenser of the heat pump reaches a temperature of 61-67°C, which allows to obtain a grain temperature of up to 43°C.

Experiments conducted in Switzerland during the drying of grain with a heat pump installation with a decrease in the moisture content of corn grain from 20 to 15%, revealed great energy efficiency: energy costs are reduced by 4 times compared to the operation of the dryer on liquid fuel.

When drying grain (up to 14%) of corn with a moisture content of 33.5% with a heat pump dryer, energy consumption is reduced by 40% (at a heated air temperature of 44°C).

When the dryer operates with a fully closed cycle, when the drying agent is heated by the heat of the exhaust coolant, the energy consumption for drying is reduced to 71%.

The use of heat pumps in combination with solar collectors allows to increase the drying efficiency.

Reduction of fuel consumption by thermodynamic methods is possible mainly by reducing the heat emissions of the grain dryer (its grain drying part).

The method of infrared irradiation is one of the promising physical methods of food processing. The use of infrared radiation significantly reduces the duration of heat treatment, due to the lack of thermal resistance of the boundary layer of the product to the radiant flux, the energy of which is directly absorbed by the surface of the raw material particles. At the same time, infrared radiation is actively absorbed by water contained in the product, but is not absorbed by the fabric of the product that is dried or heat treated. Therefore, moisture removal is possible at low temperatures (40 ... 60°C), which makes it possible to maximize the preservation of vitamins, biologically active substances (BAS), natural (natural) color, taste and aroma of products that are subject to drying or heat treatment. It should also be borne in mind that radiation drying has the lowest specific energy consumption.

Although considerable attention is paid to the study and application of infrared radiation in various fields of technology, the introduction of this progressive method into the practice of food production is slow. The design of technological equipment under the condition of infrared energy supply is a rather complicated and time-consuming process, which is impossible without a developed methodological basis. The developed methods of calculation of certain types of IR installations cannot adequately describe a wide range of IR equipment and solve many types of problems arising in food processing.

For the installation with infrared irradiation of oil material, hardware and design features at the levels of functional and structural elements and functional and structural units are determined by the following conditions: firstly, they must provide (taking into account the initial technological factors of the processing object) the required level of activity of anti-nutrients and humidity; secondly, constructive solutions for the organization of infrared irradiation, providing the necessary energy and technological efficiency of the process.

A number of experimental studies were conducted to prove the effectiveness of using infrared radiation for drying oilseeds.

During the processing, the product is placed on a metal grate, under which there are generators of infrared radiation. The essence of the process of processing food raw materials in the field of infrared irradiation in an open working space is that electromagnetic waves from the radiation source penetrate the product to a depth of 2 mm and are partially or completely absorbed in it. In this case, electromagnetic energy is converted into thermal energy, which causes heating of the product. In addition, the product is heated convectively, i.e. by the hot air of the working space (175...350°C), and conductively - by the surface of the grate of the apparatus.

As a rule, the processing process in the infrared equipment consists of two stages: the first stage is the processing of the product at the maximum temperature of the infrared irradiation source until the formation of a browning crust on the surface of the product; the second stage is bringing the product to full readiness at a reduced constant temperature of the generators. Reducing the temperature at the second stage is carried out by reducing the electrical power or increasing the distance of the product to the source of infrared irradiation. Design solutions for the layout of the IR lamp unit and the generators themselves ensure the achievement of uniform irradiation in accordance with the requirements of processing the corresponding oil-containing material, including the content of anti-nutrients.

The results of experimental studies conducted by us show that the reduction of product moisture from the involvement of an IR irradiator is effective. In addition, it was found that an increase in the specific loading of both crops to 7.5 kg/m^2 leads to an increase in moisture yield, and a further increase in the specific loading is inappropriate, because moisture extraction does not increase (when drying rapeseed), or, in general, decreases (when drying soybeans), which can be explained by the insufficient penetration of infrared rays into the entire loaded product (Figure 1).

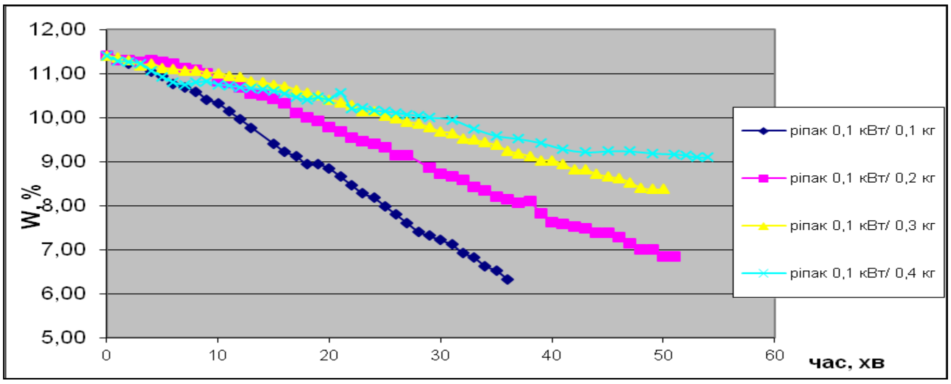

Figure 1 - Dependence of moisture reduction on loading for rapeseed at constant power.

From these graphs it can be seen that with a smaller load of products moisture is removed faster and more completely due to the good penetration of infrared rays into the grain layer.

According to the results of these studies, it was found that drying using an infrared irradiator at a power of up to 300 W leads to a gradual and complete evaporation of moisture, but it takes more time; in contrast, increasing the power to 400-500 W leads to faster moisture extraction, but the product is heated faster to the critical limit, which can significantly worsen its properties (Figures 2-5).

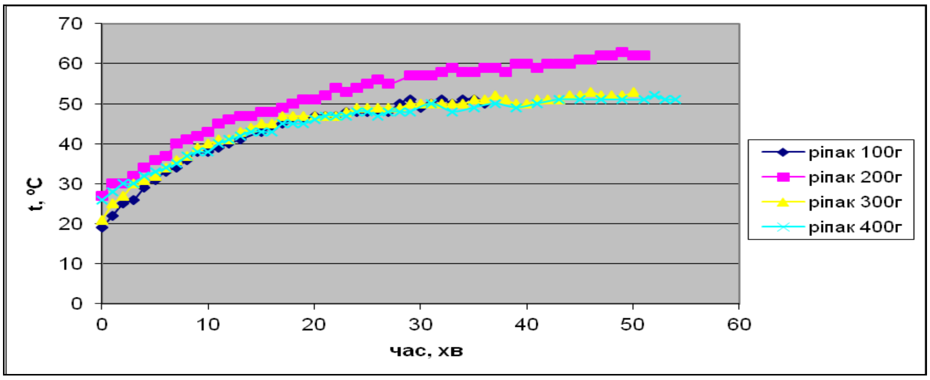

Figure 2 - Thermograms for rapeseed at variable input.

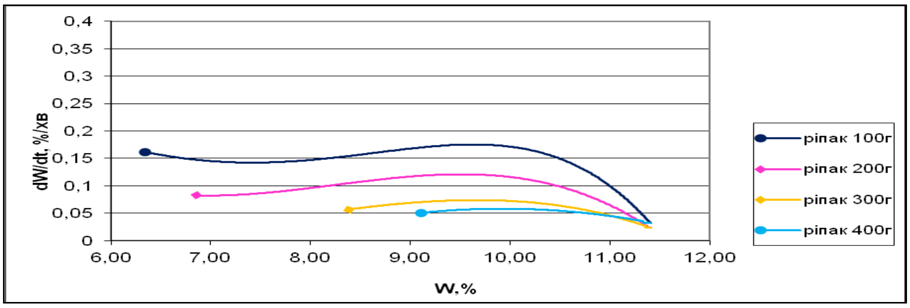

Figure 3 - Drying lines for rapeseed with variable loading.

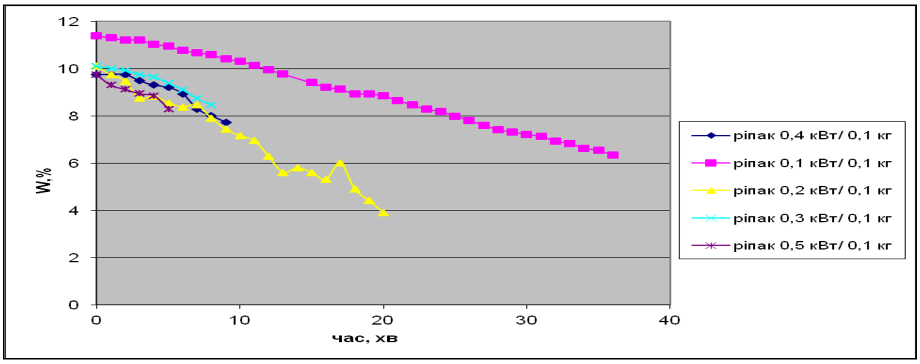

Figure 4 - Drying kinetics at constant chamber loading and changing the power of the infrared field for rapeseed grain.

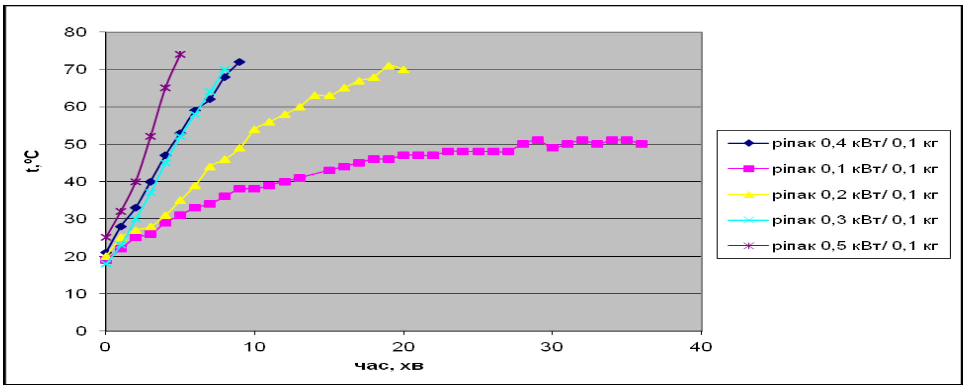

Figure 5 - Thermograms for rapeseed at variable power.

From these thermograms it can be seen that at a power of 100 W the heating of products is gradual, but it takes a lot of time. When using a power of 200 W, there is a sufficiently gradual heating with much less time. At a power of 300 W and above, the products are heated very sharply.

It is best to use a power of no more than 100 watts. At the same time, the moisture removal rate is high enough with no risk of product damage due to sharp heating to critical temperatures (Figure 6).

When drying soybeans with different loads, the tendency to increase the moisture yield and drying speed at lower loads was also preserved. At loads of 100 and 200g, the moisture yield rate is significantly higher than at 300 and 400 (Figures 7-9).

The graphs show that the fastest and less energy-consuming removal of moisture from soybeans occurs at a power of 400 W.

To study the influence of technological, energy and design parameters under IR irradiation on the efficiency of moisture removal from the product, an experimental installation was created, the scheme of which is shown in Figure 10.

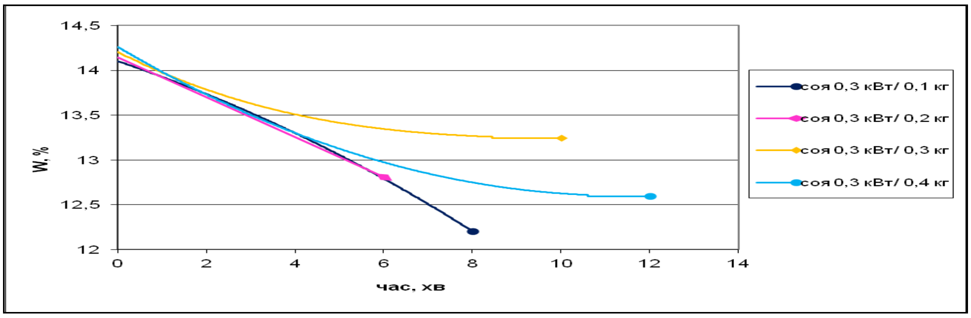

Figure 6 - Dependence of moisture reduction on loading for soybeans at constant capacity.

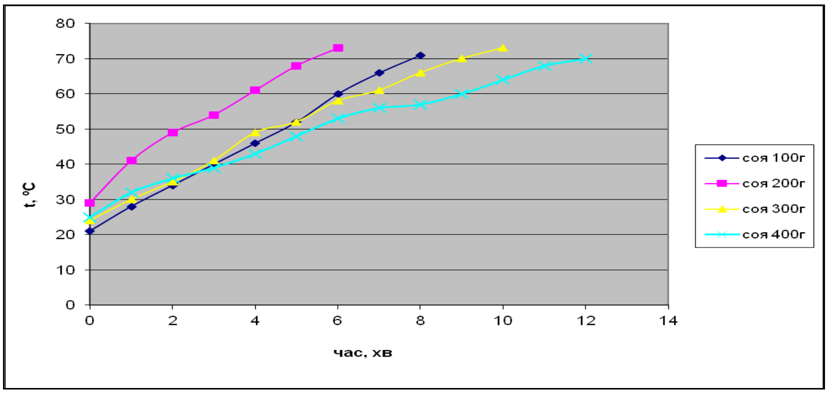

Figure 7 - Thermograms for soybean seeds at variable loading.

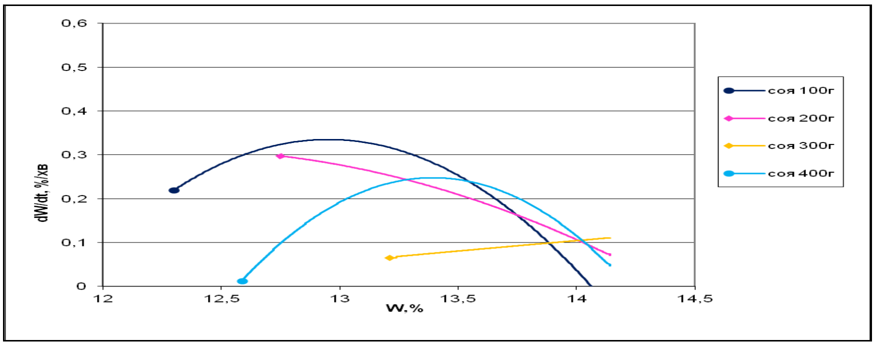

Figure 8 - Drying lines for soybean seeds with variable loading.

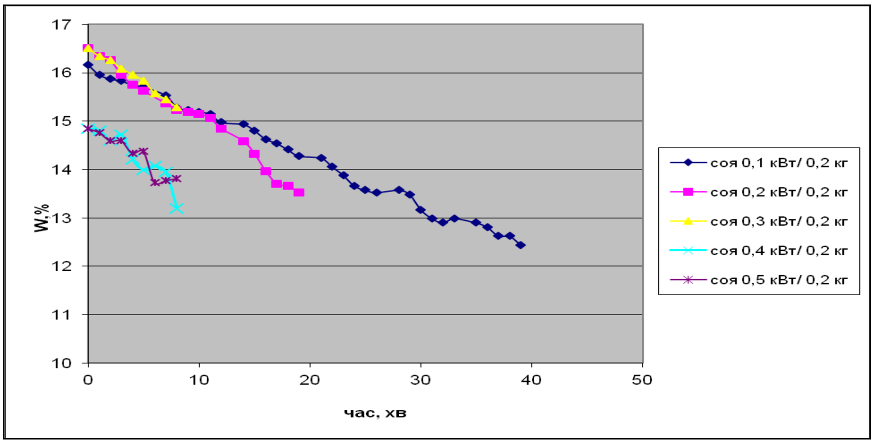

Figure 9 - Dependence of moisture content on power for soybeans at variable power.

It works as follows: a certain amount of whole grain of rapeseed or soybean is fed to the belt, obtaining a specific loading value equal to 1.5; 3.5; 5 kg/m^2, respectively. After that, the belt was set in motion at a speed of 0.13, 0.33 or 0.54 cm/s. During the movement of the belt under infrared radiators, the products were exposed to irradiation of a certain power of 100, 200, 300W. At the same time, one, two or three emitters were turned on along the belt.

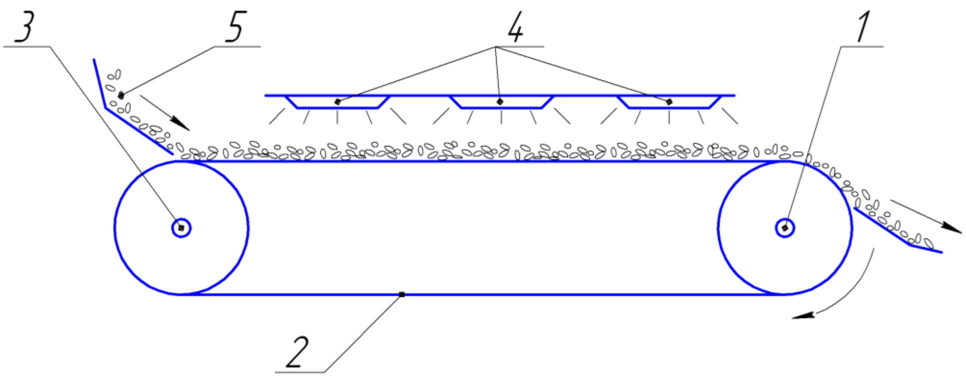

Fig. 10 - Scheme of the experimental conveyor installation for IR drying:
1 - drive roller; 2 - belt; 3 - tension roller; 4 - infrared irradiators; 5 - products.

According to the results of the research, it was found that the optimal power for irradiators is 200 W, and the specific loading of more than 3.5 kg/m^2 is inexpedient to use because a large layer of products does not allow infrared rays to process all the grains, especially at high enough belt speeds. The power limit is set because increasing the power above 200 W can damage the product due to high temperature, and the use of several irradiators gives a greater drying effect than one, but with greater power. Moisture extraction with the help of several radiators is more effective because the nature of the process is determined by the mechanism of moisture transfer in the material and the mechanism of moisture transfer from the surface of the material to the environment through the surface layer, which is located near the surface of the material. Therefore, drying in several stages prevents the formation of a crust on the surface of the material, due to which the process of moisture transfer will slow down. And short breaks between drying stages allow moisture to be distributed from the middle of the material to its surface.

Conclusions.

The number and designs of grain dryers with various devices for utilization of exhaust gas heat: heat exchangers, heat pumps and other equipment to reduce the moisture content of the drying agent, which is reused. But for reasons of thermodynamic efficiency, it is necessary to deal with the reduction of heat emissions into the atmosphere as efficiently as possible.

Also, we have created an experimental installation to study the influence of technological, energy and design parameters under infrared irradiation on the efficiency of moisture removal from the product.

It was found that the optimal power for irradiators is 200 W, and the specific loading of more than 3.5 kg/m^2 is inexpedient to use due to the fact that a large layer of products does not allow infrared rays to process all the grains, especially at high enough belt speeds.

It was also found that an increase in the specific loading of soybean and rapeseed crops to 7.5 kg/m^2 leads to an increase in moisture yield, and the subsequent increase in the specific loading is impractical, because moisture extraction does not increase (when drying rapeseed), or, in general, decreases (when drying soybeans), which can be explained by insufficient penetration of infrared rays into the entire loaded product.

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Анотація. *В статті проводиться детальний огляд технологій та технік сушіння зерна. Звертається увага на трансформації аграрної промисловості в умовах війни.*

Однією із основних проблем забезпечення якісним зерном є його зберігання. Поряд із перспективними методами підготовки зерна до зберігання, особливу увагу представлено методу ІЧ-опромінювання, як одному із фізичних методів обробки харчових продуктів. За умови застосування ІЧ-випромінювання значно скорочується тривалість термічної обробки, що обумовлено відсутністю термічного опору пограничного шару продукту променистому потоку, енергія якого безпосередньо поглинається поверхнею частинок сировини. При цьому ІЧ-випромінювання активно поглинається водою, яка міститься у продукті, але не поглинається тканиною продукту, котрий висушується або проходить термічну обробку.

Ключові слова: *сушіння, зерно, інфрачервоне випромінювання, вологість, потужність, соя, ріпак.*

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