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Innovative methods of drying rapeseeds using microwave energy

Abstract: Rape is an important oil crop with a wide range of uses. Harvested rapeseed must be cleaned and dried before processing. The process of drying rapeseed as a small-seeded crop has its own specifics. One of the new drying methods is the use of microwave radiation, the disadvantage of which is uneven heating of the product. The purpose of this work was to study the modes of drying rapeseed by electromagnetic radiation in the ultra-high frequency range in combination with filtration. The indicators of the intensity of oilseed drying by infrared irradiation on the experimental stand were determined. The analysis of the conducted studies showed that the temperature of seeds at the maximum microwave power rises in general 1.5 to 1.8 times faster than at half the power. The higher the seed moisture content is, the higher the rate of temperature increase. After each blowing cycle, which lasted for five seconds, the temperature of the rapeseeds was set higher than the previous temperature, and after increasing the blowing time up to fifteen seconds, the temperature decreased by 8–12°C and cyclically stabilized. The applications of microwave drying represented in the paper

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are environmentally friendly, since the seeds do not come into direct contact with the products of gas combustion, which deteriorate its quality due to the possible penetration of carcinogenic components into the products. Experimental data was taken into account when developing the design of a small-sized grain dryer for farms, in which the drying process takes place without heating the air as a heat carrier.

Keywords: rapeseed, microwave energy, filter drying, temperature

Introduction

Rapeseed is a key source of edible vegetable oil and vegetable protein among four major global oil crops (Kotov et al. 2019; Kaiser et al. 2022). Rapeseed seeds are rich in lipids, which can provide the body with energy, essential fatty acids and various related lipids, such as phytosterols, vitamin E and squalene (Paziuk et al. 2021; De Oliveira and Yu 2022). Rapeseed oil and rapeseed meal are produced by processing rapeseed, in which rapeseed oil is an important source of health-promoting compounds such as polyphenols, phytosterols, and tocopherols in the human diet (Yang et al. 2019), while rapeseed meal is the basic material for a variety of commercial products such as feeds and fertilizers (Lannuzel et al. 2022). The main technological process for preserving the properties of seeds is drying (Paziuk et al. 2018). The grown rape crop must be cleaned and dried before it is processed.

Energy consumption, environmental problems and product quality are urgent problems related to seed-drying processes. It is necessary to pay attention to the development of new designs of energy-efficient seed dryers (Kuznietsova et al. 2020; Bezbah et al. 2022). At the enterprises, the drying of vegetable raw materials is performed with hot air or flue gases on convective drying units (Paziuk et al. 2022). The efficiency of convective dryers is 40%. Energy consumption of convective dryers reaches 8 MJ/kg of removed moisture, which is almost three times higher than the physically necessary minimum (Spirin et al. 2022). The content of carcinogens in the drying agent and the product is not controlled (Burdo et al. 2019). However, there is no special technological equipment for drying rapeseed, so the process is performed on grain drying equipment. Existing grain dryers do not fully meet the requirements for the quality of dried seeds. The imperfect design of existing grain dryers leads to high losses (up to 50%) and a decrease in seed quality. A convective heat-supply method used in existing dryers is limited by a high drying temperature and inertia of the process, which leads to seed overheating and does not ensure the uniformity of the dried seeds. The temperature of the drying agent should be no more than +50°C, so that the crop does not lose viability. The lower the moisture content is, the lower the drying temperature should be.

One of the new drying methods is the use of infrared (Bandura et al. 2019; Bulgakov et al. 2018) and microwave radiation. Bandura et al. (2018) theoretically substantiated the processes of radiation-convective heat and mass transfer between all the defining objects inside the vibration dryer with IR-power supply. On the basis of thermal and material balances, the equations that describe the main dynamic characteristics of the drying conditions of oily grain material in a continuously operating IR dryer were determined. Due to the fact that an exact analytical solution of the presented mathematical model in the form of a system of differential equations in partial derivatives does not exist, the proposed solution allows the identification of dependencies of temperature distribution and moisture content of grain and oil-bearing material on the length of the dryer at any time.

Burdo et al. (2017) proposed technologies of targeted energy delivery for the intensification of heat and mass transfer during the processing of food raw materials. The wave technologies of the combined electromagnetic and vibrational action formed the basis of the proposed hypotheses. Mechanisms, effects and mathematical models of barodiffusion and actions of vibration fields were grounded. The numbers of wave similarity were proposed, based on which, the bases of experimental data on drying were summarized.

The use of microwaves has many advantages. The most important aspect is a decrease in the time of the thermal process (even by 50%) and a reduction in the operation costs. In addition, it allows increases in the efficiency of processes while maintaining high quality (Guzik et al. 2022). The use of microwave energy depends on various factors, including the structure of the equipment, drying conditions (microwave energy, frequency, temperature and air velocity), and material properties. The drying system can be effectively improved if these parameters are adjusted in a proper way and processing energy consumption is taken into account (An et al. 2022). The drying of rapeseed using the energy of the electromagnetic field of the microwave range is considered to be promising, since under the influence of the microwave field energy, the seeds are heated immediately in the entire volume, in which the gradients of pressure, temperature and humidity have the same directivity, which enables significant intensification of the drying process and a reduction in the risk of prolonged exposure to higher temperatures (Li et al. 2014; Zhao et al. 2017). In addition, microwave heating equipment makes it possible to design small and mobile drying units that are convenient for use in small agricultural enterprises and farms.

Qingxi et al. (2015) proved through a series of experiments, analysis and measurements that rapeseed with an initial moisture content of 15~30% can be dried to achieve a safe storage level of moisture by changing the ratio of quality and power G, temperature T, heating time t and the load cycle Dc, respectively, while its seed value was still guaranteed. Field trials have shown that the quality of offspring remained the same and productivity increased slightly; drying in a microwave oven can activate canola seeds and increase their ability to germinate.

Based on Maxwell's equations, Oliveira and Franca (2002) simulated on-off MW irradiation in combination with sample rotation and found that this combination provided more uniform temperature profiles compared to each method applied alone.

The main disadvantage of microwave drying is its uneven heating, in particular overheating at the edges of the sample (Li et al. 2011). Due to the uneven distribution of energy in the microwave (MW) cavity, microwave-based heating applications remain a significant obstacle. A microwave conveyor belt dryer with a continuous power control using multiple

2.45 GHz MW sources improves heating uniformity. Due to sequential control of the input power of microwave sources, the electric field and temperature fluctuations, hot and cold spots in the microwave cavity were significantly reduced. Experimental results have shown that MW heating using the proposed continuous method with adjustable power can achieve about 34% better heating uniformity compared to the simultaneous multiple input method (conventional mode) (Bae et al. 2017). The research by Hemis et al. (2015) indicated that rapeseed can be safely dried at a temperature of 55°C, while maintaining up to 90% germination. In order to increase the drying rate while preserving seed viability, a hybrid microwave (MW) convective dryer was used in the study. Hybrid dryers provided more uniform heating and rapid moisture transfer within the product, keeping the product cooler and more viable (Hemis et al. 2015). Apolinar and Joaquin (2012) developed a mathematical model of grain drying in a continuous vibrating fluidized bed dryer. Simple equipment and material models were used to describe the process. The plug-flow equipment model was used to study a thin layer of particles moving forward and well mixed in the direction of the gas flow, which created a uniform color of the product during heating.

To overcome these disadvantages, we suggest a combination of drying in a microwave oven with other drying methods.

The study of the rapeseed drying process aimed at solving the problem of preserving product quality and increasing the efficiency of the drying process is an urgent and important scientific and technical task. Furthermore, in order to develop modern high-performance equipment for rapeseed drying and to justify rational drying modes, it is necessary to study the process of rapeseed drying using traditional as well as new, more efficient drying methods.

The purpose of the work was to study the modes of rapeseed drying by electromagnetic radiation of an ultra-high frequency range in combination with filtration.

1. Materials and methods

Due to the insufficient information on the effect of microwave radiation on seed raw materials, an experimental stand was created to study the kinetics of the drying process of dispersed systems. The scheme of the experimental stand is shown in Figure 1.

The experiment was conducted according to a periodic scheme: at first, microwave treatment of the product was performed, then the cassette with seeds was blown with air and weighed. Using the ADC module and thermocouples, the temperature of the product, the duration of the microwave treatment, and the air velocity were measured.

In the experimental stand, LG 2M226 magnetrons were used with the following characteristics: LG 2M226 magnetron; frequency (at the agreed load) of 2,460 MHz; average output power (at the agreed load) of 1,500 W; dimensions of the cassette (l/w/h) of 140/129/96 mm; cooling – air, forced.

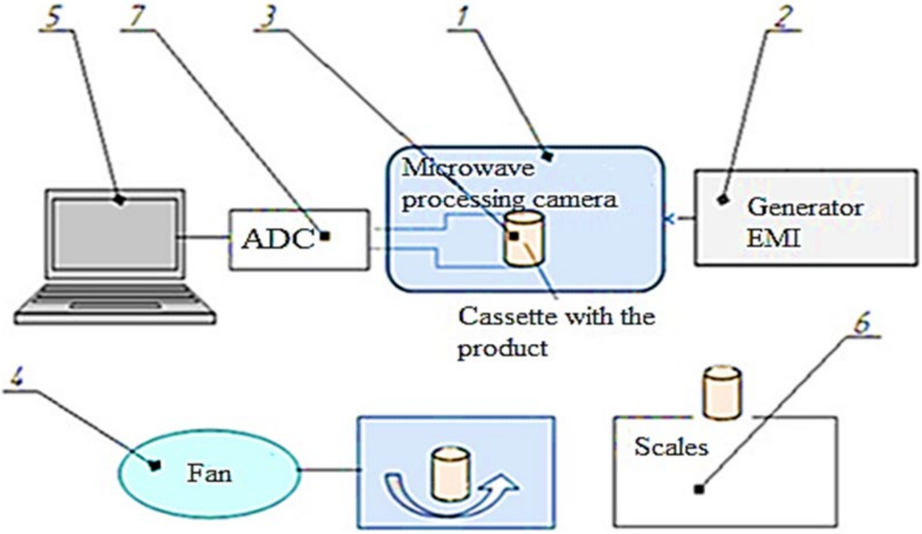

Fig. 1. Design scheme for conducting studies of the installation with microwave energy supply in combination with filter drying:
1 – microwave processing camera, 2 – electromagnetic field generator, 3 – cassette with the product, 4 – fan, 5 – computer, 6 – scales, 7 – analog-to-digital converter (ADC) module

Rys. 1. Schemat projektowy przeprowadzenia badań instalacji z zasilaniem mikrofalami w połączeniu z osuszaniem filtrów

LG 2M226 magnetron is a typical device for the use in household appliances, it is characterized by a fairly high power of microwave radiation (~ 1,500 W) and a low cost (~ 350...500 UAH), which in the case of industrial use, means that is can be classified as being consumable.

Experiments on drying rapeseed in the installation with microwave energy supply are shown in Table 1.

Table 1. The range of measurement values

Tabela 1. Zakres wartości pomiarowych

Product	Duration of microwave heating	Duration of air blowing	Microwave power	Grain moisture content, initial
	s	s	kW	%
Rape	0…300	5–15	0.24…0.8	12….20

Radiation power was set using standard means of the control panel of the microwave heating camera, which enables setting the radiation power as a percentage of the maximum power of the emitter. To conduct a series of experiments, the values of 30, 50, 70 and 100% power corresponding to 240, 400, 560 and 800 W of microwave radiation of the generator were chosen. The change of the power indicator to the maximum value and the magnetron control scheme were provided using pulse-width modulation and as a control tool during the experiments, the operation of the emitter was timed according to the indicators of the microwave radiation indicator with further calculation of the relationship between the time of operation of the emitter and the time of stops.

Rapeseed samples weighing 200 g were placed in a cassette, which created a specific load of 5 kg·m^{-2}. The cassette was then placed in an experimental setup with a microwave emitter and immediately exposed to radiation. The research was conducted according to a periodic scheme, at first the effect of microwave radiation on the product was performed and then the cassette with the product was blown with air and weighed. Using the ADC module and thermocouples, the product temperature, the duration of the microwave treatment and the air velocity were measured.

Grain moisture content was measured using a RM-600 digital moisture meter and a Wile type moisture meter.

The experiments were conducted in the summer. The ambient temperature was 25–27°C. Therefore, sharp temperature changes were not observed and there was therefore no significant impact on the drying process.

2. Results and discussion

According to the graphs shown in Figure 3, when the power of electromagnetic radiation decreases, the rate of the temperature rise also decreases. At a power of electromagnetic radiation of P = 400 W, the temperature curves are more gentle. In addition, at this power level, the decrease in the intensity of the temperature increase begins at a temperature of 62 to 72°C.

According to the graphs shown in Figures 2 and 3, the seed temperature at a microwave power level of P = 800 W, increases are generally 1.5 to 1.8 times faster than at a power level of P = 400 W. Thus, the dynamics of rapeseed heating during microwave drying significantly depends on the power of the supplied electromagnetic radiation. As the power of electromagnetic radiation increases, the intensity of the temperature rise also increases.

At the second stage of the study, rapeseeds were exposed to microwave radiation and blown with air.

Thermograms during rapeseed drying are of a stepped nature (Figs. 4 and 5); this is caused by the fact that the blowing of the material layer was conducted periodically.

The thermogram of rapeseed heating (Fig. 4) corresponds to a 5 s period of blowing and a 5 s exposure to microwaves. The thermogram of rapeseed heating (Fig. 5) corresponds to a 15 s blowing period and 15 s exposure to microwaves.

The temperature of seeds was kept close to the technological requirements at the level of 50°C.

Rapeseed temperature in Figure 4 corresponds to a blowing period of 5 s, and exposure to microwaves for 5 s; the temperature of rapeseeds in Figure 5 relates to blowing for 15 s, and

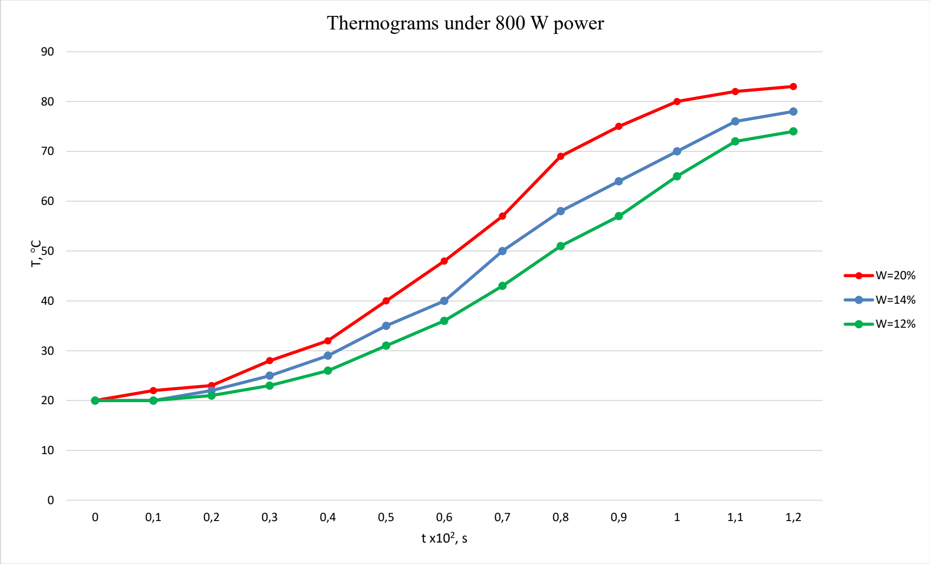

Fig. 2. Dynamics of heating rapeseed having different moisture content under the influence of electromagnetic emitter with 800 W power

Rys. 2. Dynamika nagrzewania nasion rzepaku o różnej wilgotności pod wpływem emitera elektromagnetycznego o mocy 800 W

Fig. 3. Dynamics of heating rapeseeds having different moisture content under the influence of electromagnetic emitter with the power of 400 W

Rys. 3. Dynamika nagrzewania nasion rzepaku o różnej wilgotności pod wpływem emitera elektromagnetycznego o mocy 400 W

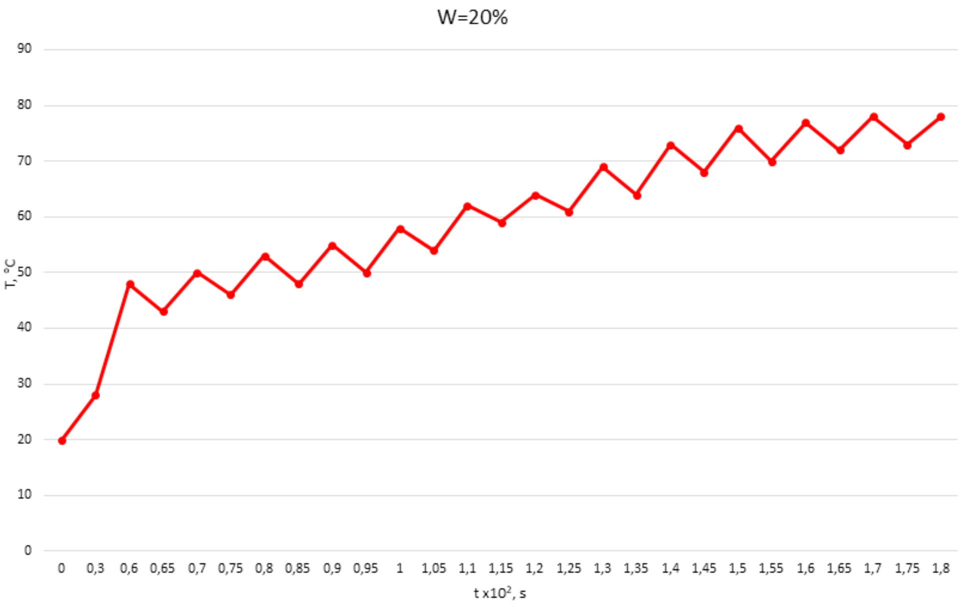

Fig. 4. The change in the temperature of rapeseed having 20% moisture content under the microwave power of 800 W and the blowing period of 5 s

Rys. 4. Zmiana temperatury nasion rzepaku o wilgotności 20% pod wpływem mocy mikrofal 800 W i czasu nadmuchu 5 s

exposure to microwaves for 15 s. The analysis shows that the duration of blowing has a significant effect on both the heating temperature of the seed volume and the drying speed.

Analysis of the graphs shown in Figure 4 shows that the seed temperature change is not the same between the cycles of the drying process. After each cooling cycle, the temperature is set higher than the previous cycle. This means that the duration of blowing the seeds with air is not enough to stabilize the temperature, and therefore the temperature of the seeds increases during the next supply of microwave energy.

In addition, a gradual increase in temperature was observed under further extension of the blowing stage. This nature of the temperature change was also confirmed by the results of studies on the drying kinetics (Fig. 4).

The studies of drying kinetics performed using this scheme made it possible to establish optimal ratios of the duration of the drying stages, in which the microwave heating of seeds to the required temperature was conducted in the first stage, and blowing with cooling by 8...12°C from the set drying temperature was performed in the second stage. When the seeds were cooled to 3 to 5°C, uneven cooling and mixing of the seeds was observed due to insufficient air supply by the fan in a short period of time.

Under the values selected, the duration of the first and second stages is approximately the same and is 1.8 to 3 minutes, depending on the microwave energy. The conditioned seed moisture of 7 to 8% is achieved in 8 to 12 cycles, depending on the initial moisture content.

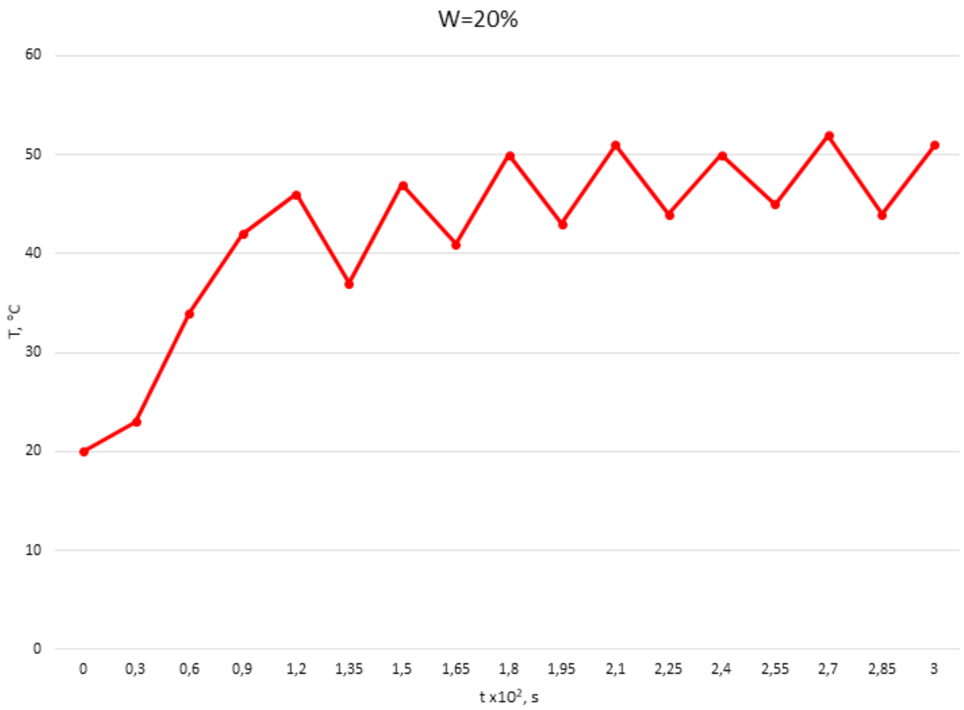

Fig. 5. The change in the temperature of rapeseed having 20% moisture content under 400 W power of microwave energy and the blowing period of 15 s

Rys. 5. Zmiana temperatury nasion rzepaku o wilgotności 20% pod mocą energii mikrofal 400 W i czasem nadmuchu 15 s

To ensure a normal heat treatment process (warming up and drying), a number of conditions must be met: a uniform supply of heat to the entire area of the seed layer; the constant removal of moisture formed on the grain surface (constant supply of dry air and removal of moist air). The fulfillment of these requirements (conditions) is directly related to the installation parameters: first of all, to the heat transfer parameters of the elements, which in a certain way characterize the heat source and determine its operating modes – temperature, power consumption; the nature of temperature distribution according to the volume of the grain layer, the thickness of the grain layer, the consumption of the drying agent, etc. In addition, the drying process is also influenced by the condition of the environment, namely the temperature and humidity.

On the basis of the conducted research, the authors developed a small-sized seed dryer. The structural and technological scheme of the proposed dryer is shown in Figure 7.

On the base 1, a pressure fan 2 is installed, which is further connected to the gas distribution mechanism 5, which includes a pressure chamber 4, a number of air ducts with rotary valves 7, connecting the pressure chamber with sections of the gas distribution grids 8 of the drying chamber 9, the longitudinal slope of which can be regulated. At the beginning of the drying chamber, a hopper for raw materials 10 is installed, and on the opposite side, there is an outlet device 11

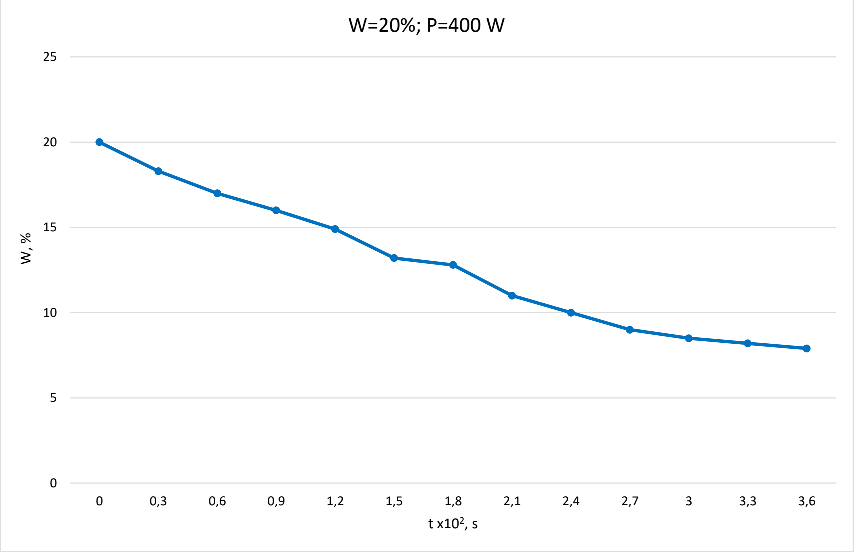

Fig. 6. Kinetics of the rapeseed drying process using microwave energy with periodic cooling by 8–12°C from the drying temperature under the power of 400 W and initial seed moisture content of 20%

Rys. 6. Kinetyka procesu suszenia nasion rzepaku energią mikrofalową z okresowym schładzaniem o 8–12°C od temperatury suszenia przy mocy 400 W i wilgotności początkowej nasion 20%

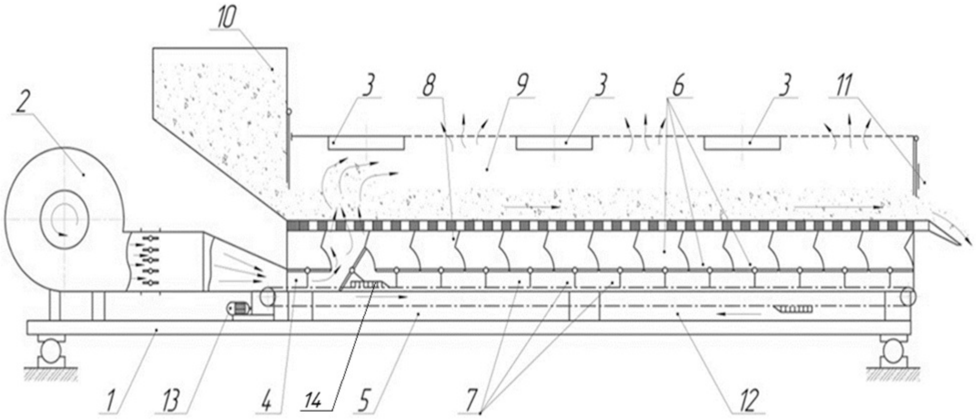

Fig. 7. Design and technological scheme of the dryer:
1 – base; 2 – fan; 3 – microwave irradiator; 4 – pressure chamber; 5 – gas distribution mechanism; 6 – sections of the gas distribution mechanism; 7 – valves; 8 – gas distribution grid; 9 – drying chamber; 10 – hopper for raw materials; 11 – output device; 12 – drive chain; 13 – electric drive; 14 – protrusion

Rys. 7. Schemat konstrukcyjny i technologiczny suszarni

for the exit of dried seeds. On the outer part of the pressure chamber, there is a chain transmission 12, on which protrusions 14 are fixed. The protrusions serve to open the dampers.

The dryer operates in the following way. Wet rapeseed from hopper 10 enters gas distribution grids 8 with a certain thickness of the layer. Drying chamber 9 is installed with the required inclination. Fan 2, microwave irradiator 3 and chain transmission drive 13 are turned on at the same time. When moving the chain 12 with protrusions 14, the flaps 7 are opened alternately, while the heated air is alternately supplied to air ducts 6, from where it successively enters the disconnected sections of the gas distribution chain grids. As a result, the seed mass acquires a fluidized (boiling) state not on the entire surface of the gas distribution grid, but on a section.

Further flaps under the action of protrusion 14, are opened alternately, and the air supply goes to the second section. This process takes place consecutively along the entire gas distribution grid 8. As a result, a wave of boiling grain material appears which moves and at the same time mixes the product. In the process of blowing, active ventilation occurs, and drying of the material occurs under the influence of microwave energy. Seed movement during drying, and hence the duration of drying, takes place due to the combination of the inclination of the gas distribution grid and the action of fluidization. The dried seeds are removed from the dryer through the output device 11, and the exhaust air from the drying chamber 9 enters the environment.

Conclusion

- One of the new methods for drying rapeseed is the use of microwave energy in combination with filtration.
- The temperature of rapeseed at a maximum microwave power of 800 W rises in general to 1.5 to 1.8 times faster than at half of the power. The higher the initial moisture content of the seeds is, the higher the rate of the temperature increase will be.
- Rapeseed blowing should be started when the rapeseed temperature reaches 40–45°C, it should be performed for at least fifteen seconds to keep the temperature of the seeds up to 50°C. There should be 10–12 such cycles.
- A small rapeseed dryer was designed.

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Innowacyjne metody suszenia nasion rzepaku energią mikrofalową

Streszczenie

Rzepak jest ważną rośliną oleistą o szerokim zakresie zastosowań. Zebrany musi zostać oczyszczony i wysuszony przed przetworzeniem. Proces suszenia rzepaku, jako rośliny o małych nasionach, ma swoją specyfikę. Jedną z nowych metod suszenia jest wykorzystanie promieniowania mikrofalowego, którego wadą jest nierównomierne ogrzewanie produktu. Celem postawionym w niniejszej pracy było zbadanie sposobów suszenia nasion rzepaku za pomocą promieniowania elektromagnetycznego w zakresie ultrawysokich częstotliwości w połączeniu z filtracją.

Określono wskaźniki intensywności suszenia nasion oleistych za pomocą promieniowania podczerwonego na stanowisku doświadczalnym. Analiza przeprowadzonych doświadczeń wykazała, że temperatura nasion przy maksymalnej mocy mikrofalowej wzrasta ogólnie od 1,5 do 1,8 razy szybciej niż przy połowie mocy. Im wyższa wilgotność nasion, tym większe tempo wzrostu temperatury. Po każdym cyklu nadmuchu, który trwał pięć sekund, temperatura nasion rzepaku była wyższa niż poprzednia, a po zwiększeniu czasu przedmuchiwania do piętnastu sekund, temperatura spadała o 8–12°C i cyklicznie stabilizowała się. Przedstawione w artykule zastosowania suszenia mikrofalowego są przyjazne dla środowiska, ponieważ nasiona nie wchodzą w bezpośredni kontakt z produktami spalania gazu, które pogarszają ich jakość ze względu na możliwe przenikanie składników rakotwórczych do produktów. Dane eksperymentalne zostały wzięte pod uwagę przy opracowywaniu projektu małej suszarki do ziarna dla gospodarstw rolnych, w której proces suszenia odbywa się bez podgrzewania powietrza jako nośnika ciepła.

Słowa kluczowe: rzepak, energia mikrofalowa, suszenie filtracyjne, temperatura