Study of the Ratio of Heat and Electrical Energy Expended in Microwave-Convective Drying of Grain

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Abstract Nowadays, the design of the power supply of agro-industrial enterprises should be carried out considering the required installed capacity and the peculiarities of production. Thus, livestock farming involves waste, the disposal of which incurs costs. Simultaneously, preparation of feed (including drying of feed grain) is associated with significant energy costs. Thus, the availability of biogas equipment will allow synthesizing utilization technologies by processing waste into biogas and supplying energy to the equipment to carry out drying. Simultaneously, it is necessary to pay attention to technologies with reduced energy consumption for technological processes, for example, microwave-convective or infrared-convective drying of grain. These technologies have reduced energy consumption for moisture extraction, but the installed capacity of the equipment is higher than in traditional technologies. This paper aims to investigate the ratio of heat and electrical energy expended during microwave-convective drying and choose possible sources of renewable energy for implementing technological operations. The fact that grain drying is mainly carried out in the harvesting period before placing it in storage allows us to consider energy equipment as a source of thermal energy in the cold season when drying is not required.

Keywords Grain drying · Microwave field · Energy costs

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1 Introduction

1.1 Energy Costs of Heat Drying

The power supply of agricultural production facilities is associated with the study of technological processes and operations of a given farm. This is typical both for the design of new equipment and the reconstruction of existing plants and production lines. Implemented projects must be based on the energy balance of the introduced technologies of production and energy generation [15]. Synthesis of various existing generation and waste disposal technologies allows for a significant reduction of the cost of the final product. Drying can be considered an example of one of the energy-intensive processes in agricultural production since the energy intensity of agricultural production is primarily related to the cultivation of crops. The gross harvest of grains in the world is currently at 2 billion tons per year. At the same time, several processes require significant energy costs to process the resulting crop. One of the mandatory and energy-intensive processes is drying of grain to bring it to the normal amount of moisture [6, 8, 13, 14]. As one of the main technological stages of grain processing, drying is primarily characteristic of regions marked with unsatisfactory weather conditions. Although the leading grain producers(by volume) are countries with mild conditions, drying is applied to about 30–40% of the gross grain harvest.

In some regions, the use of grain dryers is required only once every 2–3 years. Simultaneously, the energy intensity of drying grain is at a very high level and is 3.5–14 MJ per evaporation of one kilogram of moisture [12, 13]. It is necessary to consider that many developers, such as Petkus (Germany), Cimbria (Denmark), Dozagrant (Russia), AVG (Russia), Stela Laxhuber GMBH (Germany), Tornum (Sweden), Altinbilek (Turkey), and provide data only on the flow rate of heat drying agent or indicate the basic capacity and do not provide data for a detailed analysis of the energy intensity of drying. This is mainly due to the influence of weather conditions under which the grain is processed and the state of the harvested crop. It should also be noted that grain harvesting and drying are mainly carried out in the warm season, which allows us to consider the sources of energy idle at this time of the year as sources of heat.

The existing and currently developing drying technologies (e.g., the use of infrared radiation and microwave fields) have lower energy costs for drying than the classic heat drying methods, amounting to 2.8–4.5 MJ for evaporation of one kilogram of moisture [12]. However, their implementation increases the share of electrical energy in the total balance of energy costs. There are works devoted to using renewable energy sources (e.g., solar energy) to prepare the drying agent and reduce the cost of grain drying [2, 9]. The existing and the plants under creation often allow for both types of energy [1, 4–7, 10, 11], which allows to consider them as energy units for grain drying technology. Additionally, these units can be used to provide heat and power for technological operations at the plant. Such operations may include decontamination and preparation of fodder, as well as the provision of daily needs.

Thus, the paper aims to evaluate and analyze the energy costs of drying grain and determine the possibility of using renewable energy sources. The following tasks are carried out:

- Experimental evaluation of the balance of electrical and heat energy during drying of wheat grain in the microwave-convective drying unit;
- Selection of possible energy installations based on renewable energy sources for the process of drying of grain.

1.2 Technologies of Intensification of Grain Drying

The improvement of grain drying equipment, aimed at increasing its productivity, leads to an increase in capital costs in most cases. In this case, the costs may be caused by the purchase of new equipment, reconstruction of existing lines, or implementation of new automation systems to implement control algorithms. Given that the primary goal of agricultural enterprises is to make profits, the development and implementation of energy-efficient technologies and equipment is a promising area for researchers. It is necessary to remember about the need to ensure the quality of the crop.

The main directions of increasing the productivity of grain drying equipment are increasing the capacity (mainly by increasing the number and geometric dimensions of apparatuses) and the use of factors intensifying the process of heat-mass transfer. As proved by the results of various studies, the use of electrophysical factors can lead to a reduction in specific energy consumption for the drying of grain [3, 12, 14]. Factors can affect the properties of the drying agent, such as the use of ozone-air mixtures or directly on the material to be treated, such as the use of thermal fields (infrared, high frequency, microwave) as well as an acoustic influence (ultrasound). These factors have both advantages and disadvantages that should be considered when designing equipment.

Currently, the work of many researchers is aimed both at intensifying the transfer of heat and moisture in the process of drying and reducing energy costs for drying. The electrophysical factors influencing the course of drying are actively considered. Many of the factors (e.g., ultrasound) have a minimal application due to the peculiarities of the penetration of the influencing factor into the material. Other factors (e.g., infrared and microwave) involve direct heating of the material. Therefore, it is necessary to develop specialized modes of operation tied to the current moisture content of the material due to the peculiarities of propagation of the above factors in the layer of the treated material, the possible high energy densities dissipated in the material, and high intensities of heating the grain of high humidity.

For agricultural producers, the choice of the performance criteria of equipment (high-intensity drying or low energy intensity drying) is related to the cost of the final product, which is associated with the cost and availability of energy resources required for technological processes and the provision of safety of the product during its processing and storage.

Table 1 Grain drying technologies

Technology	Energy intensity, MJ/kg of moisture	Production capacity, t/h	Execution	Advantages
Heat drying	5–14	4–250	Stationary; mobile	High output range
Ultrasound	4.0–6.0	0.01–0.1	Laboratory	High intensity of the moisture transfer
Ozone	3.5–5.5	0.1–5.0	Containerized; stationary; mobile	Low power consumption; disinfection
Aeroions	3.3–5.0	0.1–1.0	Stationary; laboratory	Low energy intensity
Radiofrequency drying	4.5–6.5	0.1–1.0	Laboratory	Decontamination; increased shelf life of the final product
Infrared radiation	5.0–9.0	0.1–10.0	Stationary; laboratory	High intensity of heating

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In terms of determining the direction of the study of grain drying equipment, it is worth comparing the use of electrical technology. Table 1 shows some indicators of drying technologies.

These intensifications of heat and moisture transfer require additional energy capacities. However, the balance of thermal and electric capacity can change significantly. Thus, drying in the mine dryer with a capacity of five tons per hour uses a heat generator with a thermal capacity of 440–500 kW with installed electrical power equipment of 12 kW. In our case, we will consider the unit for microwave-convective drying of grain, which allows intensifying heat and moisture transfer and carrying out the preparation of the drying agent and direct heating of the grain mass.

2 Materials and Methods

2.1 Laboratory Unit

To conduct experimental studies, the author used a laboratory unit, the process flow diagram of which is shown in Fig. 1. This unit contains six sources of microwave field (magnetrons—2.45 GHz, power—700 W). Magnetrons are powered through individual transformers. The operation mode of each magnetron is controlled by a programmable relay PR-114, which allows implementing not only continuous and pulsed modes of operation of the microwave field sources but also different operation modes of magnetrons by level. This feature is vital for accounting for the moisture

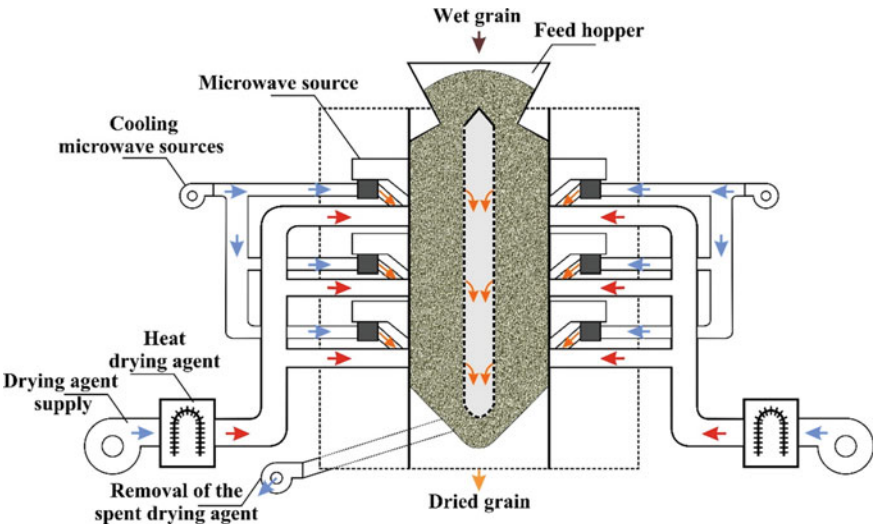

Fig. 1 Technological scheme of laboratory microwave-convective dryer of grain. *Source* Compiled by the author

loss that occurs during the movement of the grain layer along the grain pipeline. Since the moisture content in the grain decreases during drying, the depth of penetration of the microwave field and the uniformity of its heating increases. During this research, the author used modes with the magnetrons working equally on all levels.

The transformers and magnetrons were cooled in groups; the air thus heated was supplied into the drying zone, thus reducing energy losses with the exhaust air. Individual protection of magnetrons and transformers against overheating is provided to prevent emergencies. The drying agent was supplied centrally, and the drying agent was prepared in the block of flame heaters. In real conditions, the block of heat preparation of the drying agent can be implemented using electric heaters, various furnaces, recovery units, etc.

The technological process and energy consumption are controlled through a SCADA system with logging and visual presentation to the operator. In addition to the power consumption, the current temperatures of the grain layer in the drying zone are displayed to prevent disruption of the technological process. The connection is made through a common counter, which records the total costs of the technological process, which is used to estimate the specific energy intensity of the drying process or other heat treatment of the grain. The energy consumption of electrophysical sources is also evaluated in the laboratory unit utilizing an additional electricity meter. The electricity meter powers the required positions of consumers. This allows us to estimate the energy consumption for the drying process and the influence of electrophysical factors on the reduction of the specific energy intensity, as well as the share of energy consumed by them.

The presented laboratory unit allows us to estimate the energy intensity of grain processing and the intensity of heat transfer using electrophysical factors. In this case, the influence of a single factor or a combination of factors can be realized. The control of equipment operation modes (e.g., periods of magnetron activation, the delivery rate of drying agent, required temperature of drying agent, control of process parameters, and accumulation of statistical data) is carried out via the SCADA system. The MODBUS-RTU protocol provides data exchange and data logging. The details of the unit and its control system were described in previous works [3].

2.2 Conditions of the Experiment

The microwave power cycle during drying (the ratio of operating time of microwave sources to drying time) and the temperature of the drying agent were considered as factors influencing the energy intensity of drying. The magnetron activation time was set through the SCADA system and implemented through programmable relays. The cycle was 20 s. Thus, at a fraction of microwave power 0.25, the magnetron worked for 5 s, then turned off for 15 s, and the cycle was repeated. The parameters of the experiment are presented with the results in Table 2.

The current moisture content was controlled by an express method using a portable moisture meter Fauna-M and by sampling with subsequent measurement in laboratory conditions. It is worth noting that the readings of the moisture meter immediately after treatment with the microwave field do not correspond to reality due to the change in the form of bonding of liquid with the dry matter of grain. The equalization of the readings of moisture meter and indicators obtained in the laboratory occurs only after 30–40 min of treatment with a microwave field. During the unit's operation, the temperature of the grain layer in the immediate vicinity of the apertures of microwave power sources was monitored to avoid overheating of the grain above the temperatures regulated by the technological requirements. The control was carried out by fiber-optic temperature sensors OSMT-313.

Table 2 Parameters of the experiment

Mode	1	2	3	4	5	6	7	8	9
Microwave power supply cycle, p.u	0	0	0	0.25	0.25	0.25	0.5	0.5	0.5
Temperature of drying agent, °C	20	30	470	20	30	40	20	30	40

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2.3 Considered Energy Sources

We considered solar and wind energy sources and biogas plants as sources of renewable energy typical for agricultural enterprises and the regions in which they are located [13, 14]. However, in the case of wind power plants, an additional stage of preconversion of electrical energy into thermal energy would be required to provide the preparation of the drying agent, which could negatively impact the final energy balance.

Solar energy should be considered the primary energy source for regions with a sufficient number of sunny days and the required intensity of solar radiation [2, 9]. Researchers have noted the high efficiency of solar energy for the preparation of the drying agent of various products, including grains of various crops. The application of these sources may be particularly interesting for cases where the crop is harvested at a moisture content close to conditionality. This allows one to carry out drying over a long period (several days) without additional costs to intensify the process. However, in many cases, drying will need to be performed on a tight schedule, which will somewhat limit the use of this type of energy.

Livestock farms engaged in harvesting grain for fodder can consider processing into biogas with its subsequent conversion into heat and electricity [4, 7]. Since the accumulated waste of livestock products must be utilized, biogas synthesis has a high proportion of relevance for livestock farms.

3 Results

The author used the taken drying curves for the studied modes as input data for the analysis. The processing of the obtained data considered the standard parametric model and the free model set during processing. The quality of the approximation was evaluated graphically using various suitability criteria. The specified criteria include R-square and Adjusted R-square. The dependence of the change in grain moisture (W, %) on the drying time (t, min) can be represented by the following dependence:

$$W = a \cdot e - b \cdot t + c, \quad (1)$$

where:

a, b, c—the coefficients of model a, %; b, min−1; c, %.

Table 3 shows the data obtained from the statistical processing of the drying curves.

The author also determined the confidence intervals for the model and confidence bands for the approximation and the data.

Table 3 Results of statistical processing of drying curves

Mode	*a*	*b*	*C*	R-square	Adj R-square
1	3.438	0.0911	13.9	0.9819	0.9747
2	3.769	0.07893	13.48	0.9836	0.9754
3	3.293	0.09729	13.57	0.9996	0.9996
4	3.035	0.05973	14.07	0.9911	0.9889
5	3.013	0.04815	13.79	0.9864	0.9825
6	3.332	0.07748	13.81	0.9745	0.966
7	2.959	0.02602	13.95	0.9879	0.9855
8	2.99	0.04361	13.96	0.9727	0.9666
9	2.963	0.05021	13.92	0.9667	0.9584

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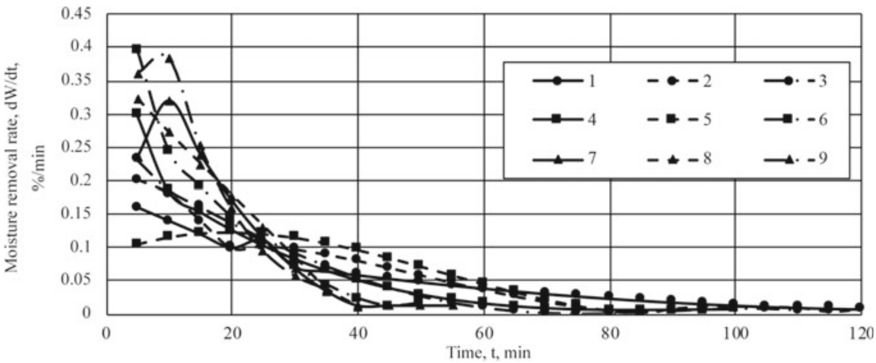

Fig. 2 Moisture removal rate during wheat drying in laboratory tests of the unit of microwave-convective treatment of the grain. *Source* Compiled by the author

At the next stages, the author obtained diagrams of moisture removal rate (Figs. 2 and 3), determined the energy consumption for moisture removal, and calculated the ratio of energy power (electrical and thermal), which are required for the operation of the unit in the considered modes of its operation. The results of these calculations are presented in Table 4. These results of determining the ratio of electricity and heat costs, together with data on available heat sources derived from renewable energy sources, will assess the possibility of energy supply of these units with different types of energy. It is also possible to determine the composition of the equipment and the required level of overlap of their capacities.

It is worth noting that the time for drying using microwave power is reduced by 2–3 times, which allows one to intensify the processing of the crop and reduce losses in case of untimely processing.

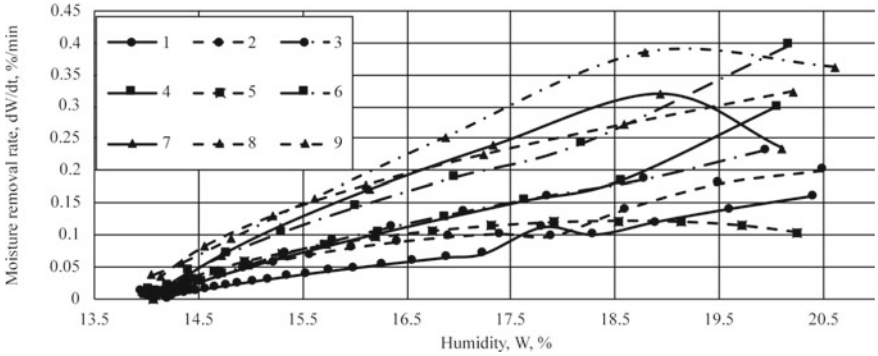

Fig. 3 Moisture removal rate at current moisture content in laboratory tests of the microwave-convective grain processing module. *Source* Compiled by the author

Table 4 Parameters and results of the experiment

Mode	1	2	3	4	5	6	7	8	9
Drying costs, MJ/kg of evaporated moisture	6.17	6.8	8.57	6.1	7.59	4.64	4.36	3.74	3.4
Heat power consumed, %	40	57	67	28	43	53	21	35	45
Electrical power consumed, %	60	43	33	72	57	47	79	65	55
Of which microwave	0	0	0	31	24	20	47	39	33
Of which ventilation	60	43	33	41	33	27	32	26	22

Source Compiled by the author

4 Discussion

The obtained results suggest that the correct choice of operating modes of equipment for the initial and current moisture content of the material can significantly affect the speed of drying and the energy consumption for its implementation. It is also worth noting that the introduction of sources of electrophysical effects, on the one hand, increases the installed capacity of the unit and, on the other hand, leads to a reduction in specific energy consumption due to the intensification of drying.

The ratio of electric and thermal energy costs suggests the possibility of using solar energy sources for the energy supply of these units. In this case, thermal energy will be used to prepare the drying agent, and electrical energy will be used to power microwave power sources and drive conveying devices. In this case, it is possible to implement stationary plants of relatively small capacity (less than three tons per hour). In this case, the electrical power will be 8–15 kW.

Mobile units based on commercially available pick-up attachments can also be implemented. In this case, it is possible to operate the mobile unit on the grain tank. Its power will be supplied by batteries or by cable from the feeding unit.

Another option is the use of biogas plants. Unlike solar installations, these units are independent of weather conditions. They can be used as a thermal energy source in the heating period and for the energy supply of grain drying equipment in the warm period. In this case, the unit will be relevant primarily for livestock enterprises. The use of biogas plants, in this case, will reduce the cost of the final product, emissions into the atmosphere, and the cost of processing and disposal of waste production.

In addition to the process of microwave-convective drying, the considered energy sources can be used during disinfection, micronization of grain, provision of daily needs of the enterprise, etc., which should be considered at the stage of design or reconstruction of specific farms.

5 Conclusion

Based on the results, the author can make the following conclusions:

- It is advisable to generate energy at the facilities of agricultural production, considering the full list of technological and domestic processes and the ratio of electric and thermal power needed;
- The share of electrical energy spent on the implementation of the technological process varies from 30 to 60% when conducting drying with the use of electrophysical influences;
- For the processes of drying crops, it is advisable to use solar thermoelectric plants and generators operating on biogas (considering the local generation of biogas from industrial waste).

The results allow choosing an available energy source for post-harvest processing based on the expected properties of the grain and the available resources of a particular enterprise.

The practical significance of this research is that the necessity of using electric and thermal energy in the operation of microwave convective drying of grain is proved. The ratio of electric and thermal energy allows for the use of local sources of energy generation.

Further research can be aimed at experimental testing of the combined operation of these energy sources with stationary and mobile units of microwave-convective drying of grain, as well as on the development of mobile devices of microwave convective treatment of the grain.

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