Improving the efficiency of convective grain drying by using low-intensity RF radiation

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Abstract. Drying (dewatering) of plant products is widely used in various technologies of their processing, transportation and storage. Existing dewatering processes and equipment are very diverse in design and application; their technical and economic performance also varies significantly. The effectiveness of the dewatering process of vegetable raw materials depends on the range of initial and final humidity and a number of physical, mechanical, chemical and other properties of the product, the drying method, technology and technical characteristics of the equipment. It is particularly difficult to ensure efficient, relatively low-energy drying of grain products, the seeds of which contain moisture in a bound form and are separated from the external environment by a dense seed shell. Currently, the volume of drying and processing of such seeds is increasing and amounts to millions of tons per season. Dried seeds are used to make flour, food additives, spices, medicinal oils and other natural products. The article studies the ways to reduce energy consumption in the main drying method-convective dewatering of commercial grain with low initial humidity. It is shown that the injection of small doses of microwave energy into the drying process - 1-5% of the total convective heating power - can reduce the overall energy intensity of the process by 25-27%.

1. Introduction

At the integral level, the process is determined by the mutual behavior of the diffusion and temperature gradients [1, 2, 4, 7]. For convection drying, the temperature gradient is always directed towards the diffusion gradient and slows down the drying process. At low humidity, the modulus of the temperature gradient is high and increases as the product dries. Because of this, the energy consumption in the process of reducing the humidity of the product continuously increases, and the drying rate decreases [3, 5, 9] (Fig. 1).

Much more promising for this zone of humidity (for example, for grain-20-14%) is the mechanism of microwave drying, in which energy is released in the volume of the dehydrated material, and the temperature gradient essentially has the same direction as the diffusion gradient. However, this method, as well as any electrical methods of drying, is difficult to implement for dewatering grain due to the lack of electrical energy sources in granaries and elevators necessary for the corresponding production processes.

To make approximate estimates, we consider a typical process of industrial grain drying. Let's say that you need to dry about 30 tons of grain per hour with about 20 to 14% humidity, that is, to evaporate about 1800 kg of water per hour. Taking into account the typical energy consumption of the microwave drying process, which in this humidity range is about 2-2.5 kW×h/kg (in terms of
evaporated moisture), the power of energy sources about 3.5-4.5 MW is required for the organization of the process. In reality, there are substations with a capacity of 250, 450, 600, and a maximum of 1000 kW in granaries and elevators, which are partially used to provide power to other production units, as well as power supply to residential and industrial premises.

![Figure 1](image)

**Figure 1.** Characteristic dependence of the energy intensity of the process $R$, kW×h/kg and of the drying rate $dm/dt$, kg/h depends on the moisture content of the product.

In this regard, the approach proposed in this paper, based on the dewatering mechanism, in which a small fraction (about 1-5%) of the drying energy is supplied in the form of microwave energy to increase the temperature of the internal parts of the volume of dewatered products and, accordingly, reduce the value, and ideally, change the sign of the temperature gradient, seems extremely promising. Obviously, devices for microwave irradiation of grain can be integrated into devices for typical convection drying in two different ways. In one case, the heat flow and the microwave energy flow should act on the dried objects simultaneously, in the second case they are to act alternately (in several stages). The latter method seems to be preferable, since it leaves more freedom for the design of combined drying equipment.

Obviously, devices for microwave irradiation of grain can be integrated into devices for typical convection drying in two different ways. In one case, the heat flow and the microwave energy flow should act on the dried objects simultaneously, in the second-alternately (in several stages). The latter method seems to be preferable, since it leaves more freedom for the design of combined convective-microwave drying equipment.

To ensure the possibility of creating the appropriate equipment, preliminary studies were conducted to identify the prospects for combining the dewatering mechanisms described above within a single technological process. At the first stage, these studies were reduced to the construction of the dependence of the energy intensity of the process on the ratio of the power of the microwave and thermal energy flows.

2. The object and method of research
The experimental setup consisted of a typical electrodynamic section based on a «grooved» [11,12] waveguide (Fig. 2). Microwave energy from microwave power sources was fed into the grooved waveguide on both sides, and a powerful stream of warm air created by a special electric heater was fed across the section from the bottom up. (Fig. 3).
The product was placed inside the electrodynamic section on a special dielectric tray, transparent to both microwave energy and warm air flows. One of the main problems in setting up such an experiment was the problem of providing a smooth (or stepwise with a small enough discrete steps) control of the microwave radiation power. This problem was solved using standard microwave energy generators with a power of 600-700 W, the energy from which was supplied to the test section through smoothly adjustable attenuators that provide attenuation in the range from 8 to 15 dB, which corresponded to a one-way energy injection from 20 to 100 W or two-way from 40 to 200 W, respectively. This made it possible to vary the power ratios of the microwave and heat fluxes in the range from 1 to 5%. The attenuators were a grooved waveguide, inside which the absorbing dielectric bodies were placed. By moving these bodies in the spatially varying high-frequency field of this system, the amount of introduced attenuation was adjusted. The approximate distribution of the field over the cross-section of the grooved waveguide is shown in Fig. 4 (the field increases from the edges to the center) [6,8,10,12].

If we move the dielectric load in this direction, the attenuation value will change smoothly. As a variable dielectric filling of the grooved waveguide, a set of water loads set in the initial position at the minimum of the high-frequency field (at the side wall of the grooved waveguide) was used. With the help of a special mechanical device, they moved in the direction of the increase in the field, while each specific position of the loads corresponded to a certain amount of attenuation of the section, and
consequently, the power of the microwave energy flow coming out of it, injected further into the experimental section.

**Figure 4.** Field distribution over the cross-section of the "grooved" waveguide

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The product (grain with a moisture content of 25-27%) weighing 3 kg was placed in a uniform layer on a pallet that was transparent to microwave energy and warm air flows. In the middle of the layer there was a special thermometer for determining the temperature of the grain. After that, the pallet was placed inside the experimental electrodynamic section. The grain drying experiment was conducted in two stages. At the first stage of the experiment, drying was carried out by a purely convection method, i.e., a powerful flow of warm air coming from a special heater with a capacity of ~5 kW acted on the product (from bottom to top). After every 2.5 minutes, the pallet with the product was placed on the scale, and a control weighing was performed, according to the results of which a graph of the dependence of the mass of the product on the drying time was plotted. The experiment on grain drying was carried out until the grain moisture reached a value of approximately 12%, (which corresponds to GOST standard for grain storage).

At the second stage, a similar portion of grain (with a moisture content of 25-28% and a weight of 3 kg) was affected by a heat flow similar in its parameters, and by microwave radiation. The power of the radiation, thanks to attenuators, could be set at a level of 5 to 1% relative to the power of the heater. For each of these levels of microwave power (5, 2, and 1%) acting on the grain together with the convection heat flow, measurements were carried out similar to those carried out at the first stage. After that, the curves for drying grain with the addition of microwave energy were applied to the graph of the dependence of the grain mass on the drying time, where a curve corresponding to purely convection drying was already constructed.
Similar experiments were carried out for wheat and rye, for a layer of grain weighing 3 kg, as well as for a weight of 7 kg with mixing of the product at each weighing. The latter operation was introduced in order to create drying conditions similar to those that exist in elevator dryers.

Taking into account the actual schemes of combined (convection-microwave) effects on the objects being dried, two different variants of the combination of microwave and thermal effects were used:
- parallel with simultaneous action of both mechanisms;
- sequential with preliminary irradiation with microwave energy in order to create a temperature gradient of the appropriate direction in the volume of finely dispersed dielectric objects subjected to energy exposure before the beginning of the convection effect.

The results of the parallel impact on wet objects of both energy flows were compared with the results of convection drying (Fig. 5), presented as the dependence of the mass of the object (initially the same in all experiments) on the time since the beginning of the process. At the same time, in the first two series with an initial mass of 3 kg for rye - Fig. 5a and wheat - Fig. 5b, the objects of bulk drying were exposed to energy flows without mixing, and in the third series with wheat 7 kg - Fig. 5c, the product was mixed at each weighing in order to improve moisture exchange. In fact, each series of experiments as a prototype had its own drying mode in real drying units.

![Figure 5](image-url)

**Figure 5.** Experimental dependences of the mass of the product on the drying time, when exposed to: 1 - pure convection energy, 2 - with an increase of 1% microwave and 3 - with an increase of 5% microwave; a) rye m=3 kg, b) wheat m=3 kg, c) wheat m=7 kg with mixing.
The results presented in Fig. 5 a, b, c were processed in order to determine the real energy intensity of each of the processes in a given range of humidity. The general approach to processing the results was as follows. Based on the results of a pre-determined humidity of $\chi_0 (%)$, the dry residue mass was determined as part of the initial mass $m_i$ of the experimental sample:

$$m_d = 100m_i / (100 + \chi_0)$$  \hspace{1cm} (1)

The starting point on the moisture waning curve $m_{20}$, corresponding to 20% humidity, and the end point $m_{12}$, corresponding to 12% humidity were defined as:

$$m_{20} = 120m_i / (100 + \chi_0)$$ \hspace{1cm} (2)

$$m_{12} = 112m_i / (100 + \chi_0)$$ \hspace{1cm} (3)

Further, the time values $t_{12}$, which corresponded to the value of the weight of the hitch $m=m_{12}$, and $t_{20}$, which corresponded to the value of the weight of the hitch $m=m_{20}$, as well as the total time of passage of the specified humidity interval, were determined on the decreasing humidity curve:

$$\Delta t = t_{12} - t_{20}$$ \hspace{1cm} (4)

Next, the total energy consumption of the process was determined:

$$R_c = (P_{\text{con}} + P_{\text{mw}})\Delta t / (m_{20} - m_{12}),$$ \hspace{1cm} (5)

where $P_{\text{con}}$ and $P_{\text{mw}}$ are the power of the convection heat flow and the injected microwave energy, respectively.

The data obtained in this way are presented as a dependence of the energy intensity of the process $R$ on the share of the $P_{\text{mw}}/P_{\text{con}}$ energy injected in the microwave process (Fig. 6 a, b). The graphs show that for the case of a three-kilogram initial weight $m=3$ kg without mixing, there is a significant decrease in energy intensity in the range of 1% $P_{\text{mw}}/P_{\text{con}}$ 2%, and with a further increase in this ratio, the decrease in energy intensity slows down. For a more correct assessment of the dependence of the reduction in energy intensity on the ratio of $P_{\text{mw}}/P_{\text{con}}$, the same figures show graphs of the dependencies:

$$dR_c / d(P_{\text{mw}} / P_{\text{con}}) = f (P_{\text{mw}} / P_{\text{con}}).$$ \hspace{1cm} (6)

![Figure 6](image_url)

**Figure 6.** Experimental dependence of the total energy intensity of the process on the fraction of the injected microwave energy and its first derivative a) rye $m=3$ kg, b) wheat $m=3$ kg.
The analysis of the obtained results shows that the most significant effect of the level of injected energy on the increase in the intensity (decrease in energy intensity) of convection drying occurs at relatively small values (1-2%). A further increase in the level of microwave energy leads to a relatively weak decrease in the energy intensity of the process. This is probably due to the fact that when the temperature and humidity gradients are relatively close in degree of influence on mass transfer, but opposite in sign, a relatively small change in the temperature gradient (due to microwave exposure) leads to a very significant change in the level of mass transfer. In the future, when the differences in the values of the «convection» and «microwave» temperature gradients become comparable or even less than the actual value of the «microwave» gradient, the decrease in the energy intensity of the convection dewatering process becomes slower and slower with an increase in the modulus of this gradient.

3. Conclusion
As a result of the conducted studies, it is shown that relatively small doses of microwave energy injected into bulk fine-dispersed dielectric objects subjected to convection (thermal) dewatering can lead to a significant (many times higher than the cost of microwave energy) decrease in the energy intensity of the convection process. It is also shown that the most effective reduction in the energy intensity of the convection drying process is observed in the range of the power ratio of the microwave and thermal energy flows about 1-2%.

With a further increase in the share of microwave energy, the reduction in the energy intensity of the microwave drying process slows down. The results obtained can probably serve as a basis for creating energy-saving technologies and equipment for industrial drying of grain and other fine-dispersed dielectric objects with a relatively low initial humidity.

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