Journal of Engineering and Applied Sciences 13 (Special Issue 8): 6570-6575, 2018
ISSN: 1816-949X

Optimal Operating Modes Reasoning of Sunflower Seeds Microwave Drying in a Conveyor Type Unit

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Abstract: The study describes the design of a new conveyor system for multi-stage grain drying, providing superhigh-frequency (microwave) heating, subsequent lying and convective cooling in the fluidbed of the dried material. Based on the results of the experiment, a regression was established between the microwave radiation and the time of its single exposure to sunflower seeds from the condition of ensuring their subsequent germination. According to the experimental test data of the conveyor unit, a mathematical model of sunflower seeds drying process was developed which allowed to determine the total heating time to achieve the required final moisture content of the material, depending on the microwave power radiation and exposure time. The optimal parameters of sunflower seeds dryingare determined by solving the problem of minimizing specific running costs.

Key words: Conveyor unit, microwave drying, microwave heating, sunflower seeds, drying operating modes, condition

INTRODUCTION

Climatic conditions in most of the territory of The Russian Federation, The Republic of Kazakhstan, The Republic of Belarus, Latvia, Lithuania and Estonia do not allow harvesting grain crops at their normal amount of moisture, so, in average up to 50% and in some years up to 80% of the grain harvested in Russia is subjected to drying. In European countries, harvesting takes place at moisture close to normal amount, that's why the problem of grain drying is not so acute (Ginzburg, 1960). These units allow providing a 5-6% moisture removal for a single pass movement. Seeds of some crops require low moisture content (7-9%) when dispatching for storage. Because of this, it is necessary to pass the grain repeatedly through the dryer which leads to high energy costs. For small farms, drying of relatively small volumes of grain in such units is economically unviable (Ginzburg, 1960; Moreno *et al*., 2017; Friesen *et al*., 2014). Therefore, units of comparatively low productivity, environmentally safe, easy to operate, low cost and energy-efficient are more promisingfor small grain-producing enterprises (Ginzburg, 1960). Practical implementation of these requirements largely depends on the type and design of the drying unit as well as the method and the drying operating mode.

The convective drying speed of materials is known to be reduced due to the temperature gradient influence (the material surface warms up more than inside) which leads to inefficient heating costs of the drying agent (Ginzburg, 1960; Sutiagin *et al*., 2017). This defect is partially eliminated by alternating the heating of the grain with its cooling (Rogov, 1988).

Unlike convective drying, the effect on the material by high-frequency currents allows the material to be heated from the inside. This leads to the emergence of a gradient of total pressure which ensures the transfer of steam inside the body and an increase in drying speed (Ginzburg, 1960; Rogov, 1988; Li *et al*., 2014). It should be into account that the excessive power and duration of microwaves exposure adversely affect the grain germination, that's why intermittent drying is used which leads to an increase in the drying time and a decrease in the productivity of the process (Rogov, 1988; Zhao *et al*., 2017).

The main problem of grain drying with electromagnetic radiation of microwave range is the use of a magnetron, power of the radiation of which depends on its periodic switching and timing aswhen the magnetron is switched on it operates at maximum power which can lead to overheating, destruction of the material structure and denaturation of the protein contained in the grain.

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A review of modern microwave equipment shows that Panasonic company managed to develop an inverter microwave heating system, a technical feature of which is the ability adjust the radiation power. Unlike a conventional microwave power supply in which the power of radiation depends on the periodic inclusion of the magnetron, the inverter microwave oven directly changes the power of the microwaves, ensuring their continuous penetration into the product.

The results obtained in the study of food products showed that cooking with the help of an inverter system does not destroy the structure of food (for example, meat fibers or vegetable textures).

Taking into account the above mentioned information, we decided to use an inverter heating system to dry the grain material in particular, sunflower seeds. The combination of technological and energy advantages with the possibility of developing equipment using a combination of microwave heating followed by convective drying makes this post-harvest processing technology development vectorfor oil seeds a promising one (Silva *et al*., 2016; Mustafayev and Smychagin, 2014; Bettega *et al*., 2014).

The aim of the research: Is to reduce the specific energy costs, to determine the influence of the inverter system of energy supply on the quality of sunflower seed by developing a continuous drying unit and determining the optimum parameters of the drying operating mode.

MATERIALS AND METHODS

The combination of microwave heating followed by convective drying was put into practice at the Bashkir State Agrarian University in the construction of a microwave conveyor system providing a multi-stage drying of grain in single pass (Motallebi, 2016; Silva *et al*., 2016, Zhu and Guo, 2017).

The dried material from the hopper tank 1 of this unit (Fig. 1) by means of the measuring device 2 and the frequency monitor of the mechanism is moved by a grid conveyor 8 with a given thickness of 5, ..., 10 cm and a speed of 0.04, ..., 0.4 m/min, successively inside several working chambers consisting from heating zones 3, lying zone 4 and cooling zone 5 and then is moved for unloading.

In zone 3 of microwave heating, the grain is heated to the desiredtemperature while warming at the center of the grain is higher than at its surface. Due to this, thermal diffusion of moisture from the center to the surface of the grain is ensured. In the lying zone 4, temperature equalization in the grain layer takes place and further moisture yield from the inner layers of the material to its surface occurs without additional energy costs. In the cooling zone 5, convective drying by blowing the material with a drying agent in a fluidbed is carried out. Atmospheric air with a temperature of 15, ..., 25°C whichserves as a drying agent can be heated to the desired temperature, if necessary. Bed fluidization ensures uniform material mixing, renewal of the phase contact surfaces and intensive moisture removal from the drying material surface. The moisture removed from the material, together with air is led out through the exhaust air system (Fig. 1). In addition, the grain material in zone 5 is cooled by 5, ..., 10°N. The grain temperature, grain moisture and the drying agent are monitored by sensors. The final temperature of the drying material is controlled by changing the air supply of the forced-draught fan 9 and pressure which is changed by overlapping the openings of the air distribution system 7 (Masalimov *et al*., 2013;

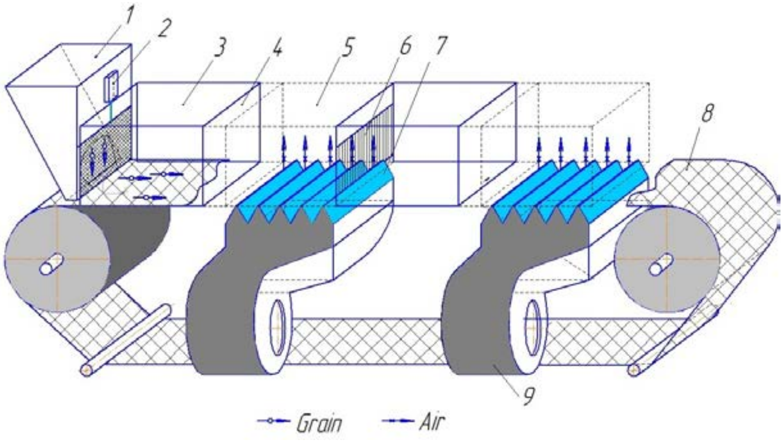

Fig. 1: Microwave grain drying unitscheme; 1) Hopper tank; 2) Measuring device; 3) Microwave heating zone; 4) Lying zone; 5) Cooling zone; 6) Leveling material depth device; 7) Air distribution system; 8) Grid conveyor and 9) Forced-draught fan

Mustafayev and Smychagin, 2014). Then, the drying material layer passes through the remaining working chambers.

A grid conveyor made of a polymer material with a cell size of 1×1 mm was used. The microwave heating zone in the drying unit is made on the basis of the Panasonic microwave oven NN-SD366W with a 2.45 GHz radiating frequency and the possibility of inverter power control of microwaves within 0.2, ..., 0.8 kW. The periods of heating, lying and cooling in the conveyor dryer were adopted in an unchanged ratio of 2:1:2. The microwave heating time of the material within 0.5, ..., 5 min was varied by regulating the speed of the grid conveyor.

The sunflower seeds of "Enisei" variety with initial moisture of 30% were studied in the research. The moisture content of the dried material was determined by the express method using a wile-55 moisture meter.

Defining the sunflower seeds germination capacity was carried out according to the standard procedure.

In the statistical processing of experimental data, the significance of the regression coefficients was determined by the student's test and the adequacy of the mathematical models was determined by the Fisher criterion at the significance level at 0.05.

RESULTS AND DISCUSSION

The efficiency of the described unit depends on the adopted drying operating modes, namely the microwave power radiation and the seed heating time. Now a days the influence of these parameters on the process of sunflower seeds multi-stage drying is not sufficiently studied. Therefore, further experimental and theoretical studies were aimed at solving these problems.

To study the effect of sunflower seeds drying on their germination capacity, a series of experiments was performed in accordance with (Table 1). The initial moisture content of the seeds was assumed equal to the upper limit when harvesting sunflower, namely 30%. It was also assumed that with high moisture, the seeds are more susceptible to high temperature. Therefore, if the drying operating modes of such seeds do not lead to a deterioration of their germination, these regimes will also be acceptable in the case of multi-stage drying of lower moisture seeds.

Statistical processing of the experimental data, corresponding to highlighted cells in Table 1 allowed obtaining the following regression Eq. 1:

$$V = 96.227+1.326.t_W-8.775.\ t_WP+4.455P^2 \tag{1}$$

Where:

V = Germination capacity (%)

t_w = Seeds heating time in working chamber (exposition time) (min)

P = Microwave radiation power (kW)

Table 1: Sunflower seeds germination capacity according to drying operating modes

	P(kW)			
t_w (min)	0.2	0.4	0.6	0.8
0.5	96	96	96	96
0.75	96	96	95	95
1.00	96	94	94	81
2.00	95	91	53	40
3.00	95	84	52	25
4.00	95	60	49	7
5.00	94	49	47	0

Limiting seed germination at 95% (1% below the maximum in the control sample) we have obtained the connection of the critical time of exposure to power:

$$t_C(P) = t_W = \left(1.227+4.455P^2\right)/\left(8.775.P-1.326\right) \tag{2}$$

Hence, it appears that in order to ensure the seeds germination, it is necessary to decrease the critical heating time t_C with increasing power. In accordance with the Eq. 2, the calculated values of t_C (0.2) ≈ 3.3 min, t_C (0.4) ≈ 0.9 min, t_C (0.6) ≈ 0.72 min, t_C (0.8) ≈ 0.71 min.

To determine the optimum drying operating modes of P and t_w, we performed a series of successive experiments at fixed values of the drying zone length 0.2 m, the grid conveyor width b = 0.38 m, the dryable layer thickness d = 0.08 m and different sunflower seeds drying schedules from initial moisture W_0 = 30 % to final moisture <8.5%. Thus, the seeds were passed through the same working chamber repeatedly until they reached 8.5% moisture content with fixed parameters of the drying operating mode (Power P and time of one seed pass t_w). In each pass the final moisture content of the seeds was measured which was also the initial one in the next pass. The average drying speed rate was calculated from the difference in the moisture content of the seeds obtained per pass and the heating time. In total, 10 drying operating modes and an additional mode with 0.4 kW and 1.5 min highlighted in Table 1 were studied. These operating modes as was established above do not lead to proteins denaturation and to significant decrease in the sunflower seeds germination capacity. The total number of observations was 485. As for each drying operating mode, a different number of passes was required to achieve a final moisture content of 8.5%, the initial data were grouped in such a way that each regime corresponded to about 10 values of average drying rates with different moisture based on the 112 observations obtained this way, statistical processing was performed and the following regression dependence was obtained:

$$\ln\frac{dw}{dt} = b_1+b_2\ln(t_W)+b_3P+b_4t_WP+b_5t_W^{1,73}+b_6Pt_W^2+ b_7P^2W+b_8P^3W+b_9Pt_W^{4,84}W \quad (3)$$

Where:

dw/dt = Drying rate (%/min)

t = The total heating time of a given seeds in the process of multiple passes through the drying unit (without taking into account lying and blowing)

The form of the mathematical model (Eq. 3) was determined on the basis of the condition for obtaining the maximum possible value of the multiple correlation coefficients R with the minimum number of significant regression coefficients. This for example, explains the grades 1.73 and 4.84 for the variable t_w. The following regression coefficients were determined: b_1 = -1.2635; b_2 = 3.07669; b_3 = 8.746; b_4 = -8.93256; b_5 = -0.784; b_6 = 2.548; b_7 = 0.1647; b_8 = -0.26938; b_9 = 0.000059 and at the same time R =0.937. Entering the symbols

$$a_0 = b_1+b_2\ln(t_W)+b_3P+b_4Pt_W+b_5t_W^{1.73}+ b_6Pt_W^2\, a_1 = b_7P^2+b_8P^3+b_9t_W^{4.84} \quad (4)$$

we have obtained the following solution of the differential (Eq. 3):

$$W = -\ln\left[e^{-a_1W_0}+a_1e^{a_0}(t-t_0)\right]/a_1W(t_0) = W_0 \quad (5)$$

Hence, the total heating time is determined to achieve the desired final moisture W_k:

$$t_k = e^{-a_0}\left(e^{-a_1W_k}-e^{-a_1W_0}\right)/a_1 \quad (6)$$

The curves for different drying schedules constructed according to Eq. 6 are shown in Fig. 2. It is easy to see that the minimum time k_k is reached at a drying operating mode of P = 0.8 kW and t_w = 0.53 min (curve 4).

As calculations have shown, this regime corresponds to a minimum t_k for all other initial moisture levels W_0 is <30%. Note that as the power P increases, the required time t_w decreases and in this case, due to the increased conveyor speed, the productivity of the drying unit is increased.

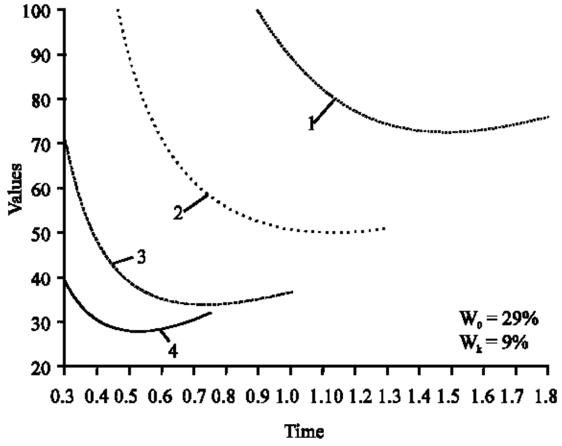

Fig. 2: Dependence of sunflower seeds drying time on the single-pass time at microwave power radiation, kW: 1-0.2; 2-0.4; 3-0.6; 4-0.8

The drying operating modes with the minimum running cost will be economically viable. To solve this problem, we express the specific running costs per 1 kg of dried material, depending on the drying schedule controlling parameters:

$$Z = \left\{\left[C_1(P/h+P_0)+C_2\right]\cdot t_k+C_3t_W\right\}/(60\cdot 1\cdot b\cdot d\cdot r) \quad (7)$$

where:

Z = Running costs, rub./kg

C_1 = Cost of 1 kW of electricity per one working chamber rub./kWh

h = Efficiency of the microwave radiator

P_0 = Power for fans and conveyor drive per one working chamber (kW)

C_2 = Amortization, maintenance and servicing expences per one working chamber rub./h

C_3 = Rubles/h

r = Dense loaded density of the dried material to moisture W_k, kg/1m^2 (m^3)

To solve the problem of bringing the seeds moisture content to the target (asymptotic) value $W_k = W(t_k)$ it is required to select the values of the control parameters P and t_w, under which Eq. 7 takes the smallest value if the following conditions are met:

$$?_{min} \le P \le P_{max} t_{min} \le t_W \le t_{max} t_W \le t_C(P) \quad (8)$$

where, P_{min}, P_{max}, t_{min}, t_{max} are respectively the smallest and largest possible values of the P and t_w parameters and the $t_c(P)$ function is determined by Eq. 2.

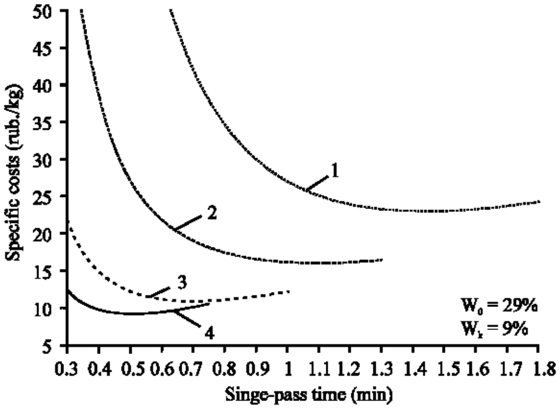

Fig. 3: Dependence of drying sunflower seeds unit costs on single-pass time of at microwave power radiation, kW: 1-0.2; 2-0.4; 3-0.6; 4-0.8

When solving the problem of minimizing a $Z(P, t_w)$ constrained Eq. 8, the following initial data were accepted: P_0 = 0.4 kW; P_{min} = 0.2 kW; P_{max} = 0.8 kW; t_{min} = 0.5 min; t_{max} = 5 min; h = 0.77; C_1 = 2.35 rubles per (kWh); C_2 = 40 rub./h; C_3 = 150 rub./h; r = 390 kg/1 m^3. The graphical solution of this problem is shown on Fig. 3, from which it follows that the Z minimum costs are achieved with a drying schedule with a heating power of P = 0.8 kW and t_w each pass duration of 0.51 min. At the same time, as calculations have shown, the optimal drying operating mode for this unit always corresponds to the largest possible value of P = 0.8 kW irrespective from the initial moisture and t_w time tends to slightly decrease with W_0 decreasing. It is easy to see that each power P, depending on the time t_w, corresponds to its local minimum specific running costs. And these costs for drying operating modes with a power of 0.2 and 0.8 kW differ by more than 2.5 times.

The comparison of the obtained sunflower seeds drying operating modes to ensure a minimum of the material total heating time and a minimum of the specific running costs (Fig. 2 and 3) show their practical coincidence. The found optimal drying operating mode also, satisfies the condition for ensuring the sunflower seeds germination capacity, since, the time of single heating $t_w$does not exceed the limit value t_c (0.8).

The researches analysis in the field of agricultural crops seeds microwave drying shows that the use of the inverter system is not sufficiently developed. In particular, researchers (Khoshtaghaza *et al*., 2015) used a microwave oven (M945, Samsung Electronics Ins which is of non-inverting type. The use of such technique leads to high energy costs, since, the magnetron works with interruptions but always at maximum (installed) power. The common tendency shows the absence of references to the researchers in terms of the use of inverter technology.

According to the results of the studies, the best layer thickness is 2.25±0.1 cm, the microwave power radiation is 300 W, the energy necessary for drying 1 kg of sunflower was 5.81 MJ. It is well known that energy consumption is taken into account for evaporation of 1 kg of moisture. The obtained results show that under the optimal regime of drying sunflower for seed purposes in the testing microwave oven the specific energy consumption was 3.6 MJ/1 kg of evaporated moisture which is 1.2 times lower than in a contact type drying units and in 1.7 times lower than in convective type dryers (Ginzburg, 1960). The height of the layer was 8±0.1 cm while the deviation of the temperature between the center of the layer and its surface was insignificant. The average moisture capacity per pass through one working chamber for the optimal regime was 0.36%. Therefore, to reduce the moisture content of sunflower seeds by at least by 5%, the microwave conveyor system should include 14 consecutively installed working chambers.

The average drying speed of sunflower seedswith moisture content from 29 to 9% in optimum regime was 0.72%/min. When drying seeds with a lower initial moisture, the average drying rate does not decrease but increases on the contrary, at W_0 = 14% it reaches 0.93% /min and at W_0 = 10% - 1%/min. This is due to the special complex structure of sunflower seeds and the drying method which realizes the alternation of microwave heating with convection drying in a fluid bed.

CONCLUSION

A regression relationship between the microwave power radiation and the exposure time of sunflower seeds is established from the condition of ensuring their subsequent germination.

A mathematical model of sunflower seeds moisture change dynamics in the process of ultra-high-frequency drying was developed.

The dependence of the specific running costs on the microwave power radiation and the sunflower seeds exposure time is established. The minimum specific running costs is achieved with a microwave power radiation of 0.8 kW and an exposure time of 0.51 min. At the same time sunflower seeds drying process occurs in almost the minimum time.

ACKNOWLEDGEMENTS

The given researches were carried out for the Bashkortostan Republic grant following the results of

young scientist's scientific researches and research groups of young scientists. The developed conveyor dryer for grain, seeds of agricultural crops and medicinal herbs was demonstrated at the 13th Russian agro-industrial exhibition "Golden Autumn" (Moscow) and was awarded with a diploma and a gold medal.

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