Journal of Engineering and Applied Sciences 13 (Special Issue 11): 8803-8811, 2018
ISSN: 1816-949X

Reasoning Barley Grain Drying Modes for Vacuum-Infrared Drying Machines

[1]Vladimir Martynov, [2]Ildar Gabitov, [3]Khasan Karimov, [3]Ilgam Masalimov
[3]Valeri Permyakov, [3]Ildar Ganeev, [3]Ilnur Saitov and [3]Bulat Saitov
[1]Department of Life Safety and Technological Equipment,
[2]Department of Automobiles and Machine-Tractor Complexes,
[3]Department of Mechanics and Engineering Graphics,
Federal State Budgetary Educational, Establishment of Higher Education
"Bashkir State Agrarian University", 50-Letia Octyabrya Street, 34, Ufa, Russia

Abstract: The study describes a construction of a new batch cereal grain drying machine. The machine operation is based on combined drying consisting in infrared heating at the ambient pressure in vacuum. Then grain is dried by the convective method and cooled by the ambient air flow when grain is discharged from the drying chamber. Experimental studies proved that the highest possible temperature of barley grain heating that doesn't result in protein denaturation is 70°C. There is a regression dependence of moisture removal on preheating and vacuum heating time, vacuum volume and the initial moisture content of barley grain resulted from the Box-Behnken second-order design for four factors. Mathematical models of drying mode optimization are developed. Parameters of a barley seed drying mode are found when solving the problem of energy cost optimization and average drying rate. Barley grain drying enhancement is found to be achieved by cutting operating costs and increasing vacuum volume.

Key words: Grain drying, barley grain, grain moisture, dryer, infrared heating, vacuum

INTRODUCTION

Climatic conditions of many European countries including Belarus, Kazakhstan, Baltic States and most territory of the Russian Federation aren't favorable to harvest grain crops at normal amount of moisture (Semenov, 2012). In some years the share of grain to be dried is 80% (Ginzburg, 1960; Moreno *et al*., 2017). Drying machines of different types and operation modes are used for these purposes.

Most of the drying methods are based on thermal action that can devitalize barley grain and its food qualities.

Designs of different drying machines for barley grain are reasonable to consider in terms of reduced temperature and mechanical effect, higher drying rate, lower energy and capital costs, less impact on the environment.

The most widespread drying systems used in agriculture are convective grain dryers as the most effective and simple. But they are of high cost, steel intensity and energy consumption (Ginzburg, 1960; Lykov, 1968; Sutyagin *et al*., 2017). Specific energy consumption of tower dryers operating on liquid and gas fuel mustn't be over 4.56 MJ/kg of evaporated moisture when drying food and industrial grain crops and 5.74 MJ/kg when drying seed grain (Anonymous, 2008). In fact, convective dryers, operating without heat recovery, expend up to 6 MJ/kg of evaporated moisture due to the fact that most of the heat is carried away irretrievably by the drying agent. When heat is recovered, the specific energy consumption of convective dryers can be reduced to 3.24 MJ/kg (Sorochinsky, 2011) that corresponds to 77.5% of the thermal efficiency.

In the Russian Federation tower and convective drum dryers have a significant disadvantage. There is grain damage in seed material drying. Moreover, grain in tower dryers is overheated that results in protein denaturation in the seed embryo (Li *et al*., 2017).

Convective grain dryers, regardless of their design, consume energy inefficiently and have low drying rate for the dryable material has a temperature gradient (Jokiniemi *et al*., 2015). This disadvantage is partly eliminated by alternating heating of the wet material with its cooling (Jokiniemi *et al*., 2015).

Corresponding Author: Vladimir Martynov, Department of Life Safety and Technological Equipment,
Federal State Budgetary Educational, Establishment of Higher Education
"Bashkir State Agrarian University", 50-Letia Octyabrya Street, 34, Ufa, Russia

Microwave and thermal radiation drying methods are characterized by penetration of electromagnetic waves inside of the dryable material that provides its internal heating (Rogov, 1988). Heating from the inside of the material is a distinct feature of microwave drying (Zhao *et al*., 2017). Therefore, the thermal diffusion of moisture from the center to the surface of the body increases the speed of microwave drying. However, during the microwave drying process when there is no control on temperature and moisture content inside the grain there is a high probability of the embryo death due to possible local overheating.

In thermal radiation drying Infrared (IR) Rays are directly absorbed by the product, thereby providing a more uniform heating of the material in depth in comparison with convective drying (Ginzburg, 1960; Lykov, 1968; Rogov, 1988). It results in a decrease in the temperature gradient and the transfer of steam from the inside to the outside under the action of the total pressure gradient (Darvishi, *et al*., 2013; Bettega *et al*., 2014; Zhao *et al*., 2017). Compared with microwave radiation, IR radiation has a more gentle temperature effect on grain, since, it is less able to warm the inner part of the grain and thus is more acceptable to dry barley grain for seed and brewing purposes. It should be taken into account that higher temperature of infrared heating can lead to damage of the grain embryo. In turn, forced decrease in the heating temperature leads to a decrease in the drying rate and, as a result to the longer drying process, lowers performance of the dryer and higher energy consumption (Rogov, 1988; Li *et al*., 2014).

After many years of improvement of all the above mentioned traditional methods of grain drying and upgrade of drying systems it is possible to state that there are practically no more ways for their further development. Therefore, the most promising is development of combined methods of drying. They have more reserves to increase efficiency of the grain crop drying process. The idea of combined drying of wet materials is not new. Using several methods of drying in different combinations is proved to be efficient by numerous studies (Ginzburg, 1960; Lykov, 1968; Anonymous, 2008). There are methods when different types of drying take place in the drying machine at once or one after another (Ginzburg, 1960; Lykov, 1968; Zhidko *et al*., 1982).

Combined contact and convective drying is being studied under the supervision of Professor Kurdjumov V.I. at Ulianovsk State Agrarian University (Ivanovich *et al*., 2013). The main disadvantage of contact drying is direct contact with the hot heat exchange surface that results in overheating of the material.

At Bashkir State Agrarian University Ganeev (2011) and Fayzrakhmanov (2015) study microwave radiation in combination with convective drying.

Scientists of the Federal University of San Carlos Bettega *et al*. (2014) Freire combine microwave and vacuum drying.

As it was said before, a common disadvantage of microwave drying is uncontrolled heating of thegrain embryo.

At Ryazan State Agrotechnical University named after P.A. Kostychev they conduct scientific researches on drying bee pollen in a vacuum-infrared drying machine that minimizes the duration and energy consumption of the drying process (Byshov *et al*., 2016).

Evaluating the existing works showed that combined use of infrared radiation and vacuum provides the drying process at low temperatures, removes up to 8% moisture for one operation, reduces the duration of the drying process and its cost (Masalimov and Karimov, 2014).

Taking into account the above mentioned ideas, we decided to use the combined effect of vacuum and infrared radiation with further convective drying of barley grain (Karimov *et al*., 2016). The noted advantages allow us to consider this direction of development of the technology of post-harvest processing of grain crops to be quite promising (Soares *et al*., 2016; Manikantan *et al*., 2014; Maier, 2017).

The aim of the study is to reduce the specific energy costs, increase thebarley grain drying speed and quality by developing a vacuum-infrared drying machine and determining the optimal parameters of the drying mode.

MATERIALS AND METHODS

Infrared heating in a vacuum environment is implemented in a vacuum drying unit developed at the Bashkir State Agrarian University. It is of a batch type where air-conditioned grain moisture is achieved at one time of processing (Anonymous, 2011). The drying process is carried out as follows.

The feeder delivers wet bulk material through the hatch 1 to the hopper 2 which is a drying chamber of 0.25 m^3 volume, divided into 3 sections by film-type IR transmitters 3 with a wavelength of 7.4 μm (Fig. 1). The programmable controller of the control unit 4 processes the signal received from the temperature and moisture sensors installed in the drying chamber, activates the IR transmitters and maintains the set temperature of the grain heating. Then the value VE260N vacuum pump 5 is switched on which creates vacuum in the drying chamber 2. After the preset heating time, the material when the screen 6 is open, passes to the air chamber 7 where it is subjected to convective drying by the active air blowing fan 8. As a result, dust and light weed seeds are blown out through the discharge opening 9 and the dried material moves along the slanting pan of the chamber 7 for discharge.

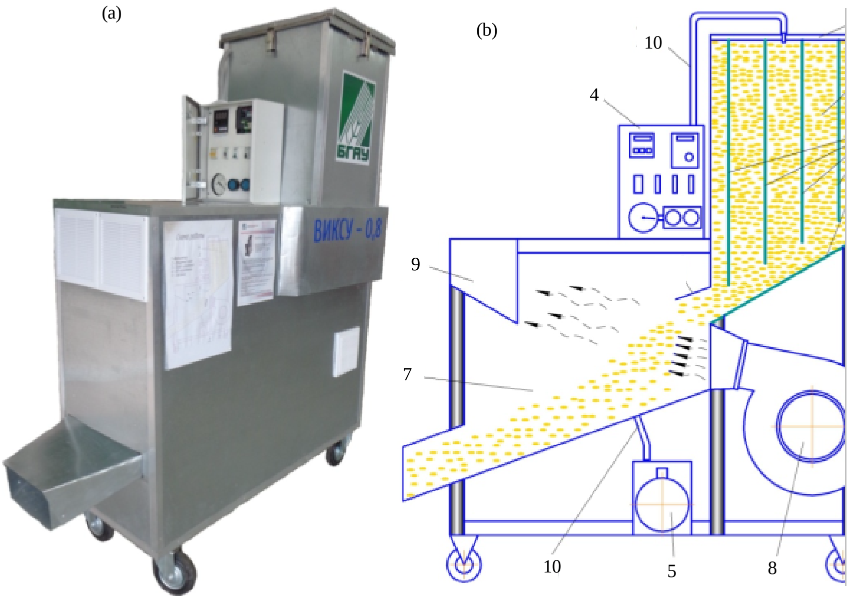

Fig. 1: Vacuum-infrared drying unit: a) General view and b) Schematic diagram; 1) Hatch; 2) Bulk material hopper; 3) IR transmitter; 4) Control unit; 5) Vacuum pump; 6) Screen; 7) Air chamber; 8) Fan; 9) Bulk material discharge and 10) Vacuum pipe

In the drying chamber the moist material is heated to a preset temperature and IR radiation heats the grain inner part intensively enough for temperature gradient not to hinder diffusion of moisture from the centre to the surface of the material in contrast to convective drying. The vacuum created in the drying chamber, firstly, increases the pressure gradient and secondly, reduces the temperature required to evaporate moisture in the material. Thus, infrared radiation in vacuum environment accelerates the grain moisture removal process at a gentle temperature. The final drying of the material is carried out in the air chamber by blowing with a drying agent which is atmospheric air at 20-25°C. The moisture that has passed from the material is forced out through the discharge opening 13.

The previous experiment found the material layer per each IR transmitter to be 25 mm thick provided the grain is equally heated. Thus, the distance between adjacent IR transmitters is 50 mm.

At a constant vacuum pump capacity of 170 dm^3/min the vacuum value was changed with the help of an adjustment mechanism by changing the atmospheric air intake channel throat. The vacuum gauge incorporated in the control unit monitored the vacuum value.

A screw type feeder T-403/2 with up to 15 t/h capacity and 2.2 kW power is used to deliver the grain to the hopper.

The barley seeds of the “Mikhailovsky” cultivar with the initial germination of 97.8 % were used. Samples of the grain dried in a vacuum infrared dryer were taken at the beginning in the middle and at the end of the discharge in each experiment which corresponded to the different arrangement of the grain in the drying chamber. Electrical moisture meter “Fauna M” was used to determine the moisture value of the grain in each sample by the express method. The values were then averaged. Grain was wetted and subjected to convective drying at the drying agent temperature of no more than 25°C to obtain the initial grain moisture.

Samples to determine seed germination capacity were taken in line with different location of the grain in the drying chamber. Germination capacity of barley seeds was determined based on standard procedures (Anonymous, 2011; Friesen *et al*., 2014).

Three or four factor experiments used Pesochinsky (Martynov, 2018; Pinchuk, 2008) and Box-Behnken (Martynov, 2018; Adler *et al*., 1976) second-order non-compositional designs with three factor variation levels (-1; 0; +1) as the basis for mathematical modeling. The experiments provided three-and fourfold replication, the order of the experiments was randomized.

Student’s test was used to determine regression ratios and Fisher’s ratio test at 0.05 significance level was used to identify the adequacy of mathematical models in the statistical experimental data processing.

RESULTS AND DISCUSSION

Efficiency of the described vacuum infrared drying machine depends on the regular drying modes, namely the

Table 1: Parameters of the experiment design of the study on grain germination

Design parameters	Coded value	Factor values at the design points T_{max} (°C)	 t (min)	 W_i (%)
Zero level	0	80	17.5	19
Variation range	1	15	12.5	3
Upper level	+1	95	30.0	22
Lower level	–1	65	5.0	16

maximum temperature of grain heating, the vacuum value, the heating time in and without vacuum. The effect of these parameters on the barley drying process is still to be considered. Therefore, experimental studies were aimed at providing the base for operation modes of drying barley grain for seed production and brewing purposes.

The zero degree limit of protein denaturation can be used as a basis for selecting drying modes (Zhidko *et al.*, 1982). The factors T_{max}-maximum temperature of heating the IR transmitter surface, t-heating time, W_i-the initial grain moisture content were taken as the three main ones affecting the viability of the grain after drying. A dependence of an increase in thermal stability of the grain upon a decrease in the grain moisture content and the time of high temperatures was used as an initial fact (Zhidko *et al.*, 1982).

Factor variation ranges were taken based on the study of the relevant literature on infrared radiation and vacuum type drying (Byshov *et al.*, 2016) as well as drying technological requirements and drying machine design features. Table 1 demonstrates the range limits of factor variation.

A three factor experiment was performed with threefold replication to investigate the effect of the factors on the germination capacity of barley seeds G in accordance with (Anonymous, 2011; Friesen *et al.*, 2014) (Table 2).

After heating the grain was dried under atmospheric conditions to moisture content of 14% and then barley seed germination capacity was tested.

Statistical experimental data processing showed that neither the heating time from 5-30 min, nor the initial moisture content of the seeds in the 16-22 % range has a significant effect on the thermal stability of barley seeds. After excluding insignificant regression ratios, the following relationship of the barley seed germination capacity and the decoded T_{max} value was obtained:

$$G = -294.15+11.7565T_{max}-0.0887T^2_{max} \quad (1)$$

The regression dependence provides an adequate description of the test data at 0.05 significance level it has a multiple correlation ratio R = 0.917 and is represented graphically in Fig. 2.

Table 2: The matrix of the Pesochinsky three-factor design

Experiment number	Factors T_{max}	 t	 W_i	Germination capacity G (%) G_1	 G_2	 G_3
1	+1	+1	0	23	4	15
2	+1	-1	0	30	9	16
3	-1	+1	0	93	98	95
4	-1	-1	0	95	99	92
5	+1	0	+1	45	9	15
6	+1	0	-1	68	15	17
7	-1	0	+1	94	96	91
8	-1	0	-1	98	95	97
9	0	+1	+1	85	58	72
10	0	+1	-1	93	75	84
11	0	-1	+1	90	91	69
12	0	-1	-1	89	93	51
13	0	0	0	91	52	87

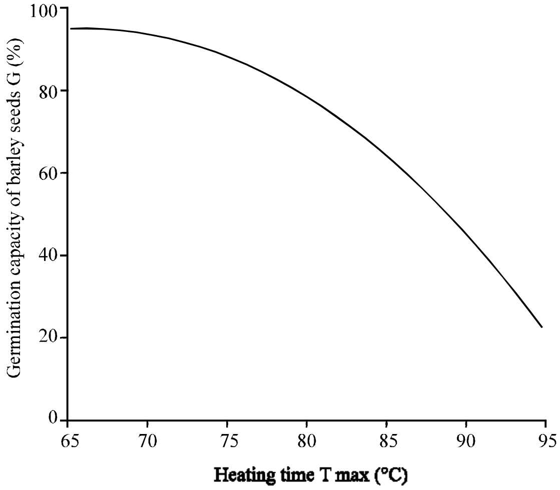

Fig. 2: Dependence of barley seed germination on the IR transmitter surface temperature

It can be seen from Fig. 2 that heating at a temperature higher than 70°C causes a significant decrease in the barley seed germination capacity. Therefore, this value is accepted as the maximum grain heating temperature which ensures maximum drying intensity that does not result in protein denaturation.

The following input parameters were taken in the experiment on establishing the optimal mode of barley grain drying: the vacuum value H; heating time without vacuum (preheating time) t_1; heating time in vacuum t_2; initial moisture content of grain W_i. The output parameter was the value of the moisture removal DW. The following factor variation ranges were taken: H (20, 80 kPa), t_1 (0; 60 min), t_2 (6, 60 min), W_i (16, 22%). The experiment was performed under the Box-Behnken design for four factors with a four fold replication (Table 3).

During the experiments, the grain was heated not higher than 70°C. A thermostat was used to maintain the required temperature of grain heating. Figure 3 shows one

Table 3: Matrix of the experiment design on establishing the mode of barley grain drying in a vacuum infrared dryer

	Factors				Moisture removal DW (%)			
Experiment number	H	t_1	t_1	W_1	DW_1	DW_2	DW_3	DW_4
1	+1	+1	0	0	5.00	4.13	4.00	4.50
2	+1	–1	0	0	2.04	2.50	2.47	2.40
3	–1	+1	0	0	2.20	2.50	1.74	2.10
4	–1	–1	0	0	1.65	1.05	1.40	1.30
5	0	0	+1	+1	5.04	5.90	5.60	5.23
6	0	0	+1	–1	1.30	1.70	2.05	1.80
7	0	0	–1	+1	2.30	2.70	1.80	2.33
8	0	0	–1	–1	0.05	0.40	0.05	0.10
9	0	0	0	0	2.70	2.21	2.00	2.43
10	+1	0	0	+1	5.10	5.60	5.90	5.63
11	+1	0	0	–1	1.85	1.50	1.15	1.53
12	–1	0	0	+1	3.58	3.10	3.80	3.43
13	–1	0	0	–1	0.75	1.00	0.35	0.60
14	0	+1	+1	0	4.35	3.60	3.97	4.10
15	0	+1	–1	0	1.44	1.20	0.80	1.03
16	0	–1	+1	0	2.20	2.84	2.31	2.53
17	0	–1	–1	0	0.20	0.05	0.09	0.07
18	0	0	0	0	2.10	2.74	2.20	2.43
19	+1	0	+1	0	5.40	4.90	4.50	5.03
20	+1	0	–1	0	0.64	1.25	0.90	0.70
21	–1	0	+1	0	2.50	2.00	2.80	2.40
22	–1	0	–1	0	0.61	0.90	0.30	0.50
23	0	+1	0	+1	5.80	5.10	4.70	5.20
24	0	+1	0	–1	1.40	1.67	1.00	1.30
25	0	–1	0	+1	2.60	3.10	3.50	3.07
26	0	–1	0	–1	0.75	0.45	0.90	0.63
27	0	0	0	0	2.71	2.20	2.00	2.43

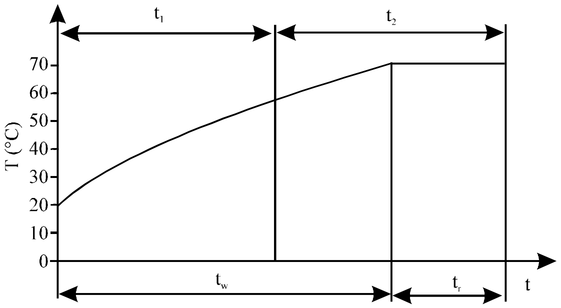

Fig. 3: Graph of the barley grain heating process in a drying machine

of the possible options for heating the grain. The period of grain heating, characterized by a temperature rise to a T_{max} value is t_w During this period, the IR transmitters operate at full power. Then, during the period t_r the IR transmitters go into a periodic operational mode and maintain a constant grain heating temperature T_{max} with the help of the heat regulator. Depending on t_1 and t_2 values grain may and may not reach the maximum temperature T_{max} both during the time period t_1 and t_2 this case is shown in Fig. 3.

Statistical processing of the experimental data Table 3 resulted in the following regression equation in the decoded form:

$$DW/W_i = b_1+b_2H+b_3t_1+b_4t_2+b_5W_i+b_6Ht_1+b_7Ht_2+b_8t_1W_i+ b_9t_2W_i+b_{10}HW_i+b_{11}H^2+b_{12}t_2^2+b_{13}W_i^2 \qquad (2)$$

where, b_1, b_2 ..., $b_{13}$are regression ratios: 0.1985; -0.003944; -0.0026953; -0.0005455; -0.02336; 0.00001857; 0.00003635; 0.00015467; 0.00014191; 0.0001181; 0.0000124; -0.0000213; 0.0007684.

The multiple correlation ratio was R = 0.979. This mathematical model provides adequate description of the entire experiment area and allows examining the effect of drying mode on a number of optimization parameters. Figure 4 and 5 demonstrate graphical dependences of the average drying speed on the studied factors:

$$DW/t = f(W_i, H, t_1, t_2);\ t = t_1+t_2+t_{tr}+tb \qquad (3)$$

Where:

t_{tr} = Time of grain charge into the drying chamber is taken for 1 min

t_b = Time of grain discharge or time of air blowing of grain by the fan is taken for 7 min

An analysis of these relationships showed that the higher the initial moisture content of the grain, the higher is the average barley grain drying speed in a vacuum infrared dryer. Shortening of the grain heating time without vacuum t_1 and a certain time value of grain heating in vacuum t_2 produces more intensive drying.

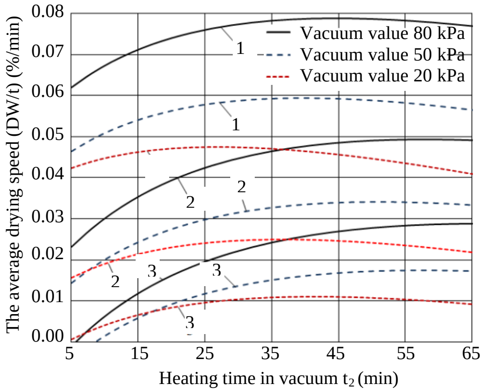

Fig. 4: The dependence of the average drying speed on the heating time in vacuum t_2 the vacuum values at t_1 30 min and the initial moisture content of the grain at: 1 22%; 1-2-19%; 3-16%

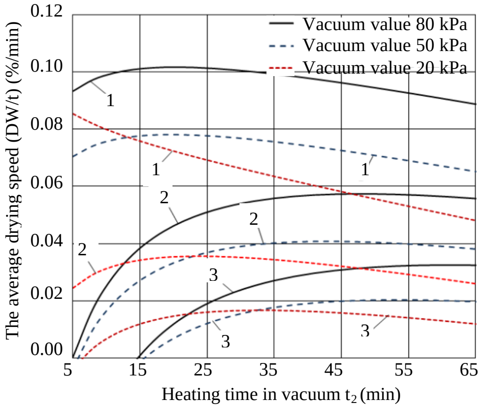

Fig. 5: Dependence of the average drying speed on the heating time in vacuum t_2 vacuum values H at t_1= 0 and the initial moisture content of the grain at: 1-22%; 2-19%; 3-16%

Further extending of time t_2 leads to a decrease in the average drying speed due to a reduction in the moisture content of the grain. Increasing the vacuum H causes an increase in the average drying speed.

It should be pointed out that the final moisture content of the grain does not correspond to the specified moisture W_f at the accepted values W_i, H, t_1, t_2 the same is true for the function extreme values presented in Fig. 4-6. It would be therefore useful to achieve the required final moisture value W_f = 14 % in the drying process in order to solve the task of optimizing the parameters H, t_1, t_2 which ensure the maximum average drying speed of grain of different moisture W_i. This will shorten the total drying time of the grain and increase performance of the drying machine.

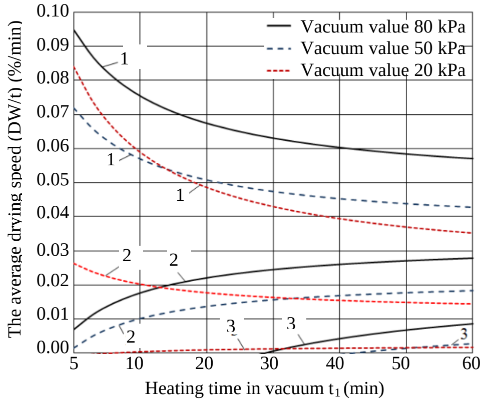

Fig. 6: Dependence of the average drying speed on the heating time without vacuum t_2 vacuum values H at t_1= 0 and the initial moisture content of the grain at: 1-022%; 2-19%; 3-16%

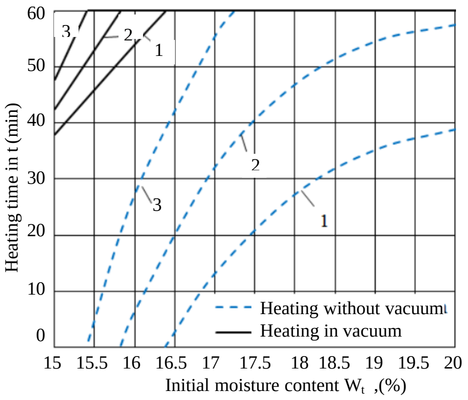

Fig. 7: Optimum grain heating time without vacuum t_1 and in vacuum t_1 depending on the initial moisture content of the grain W_1 at vacuum values, kPa: 1-80; 2-70; 3-60

"Search solution" add-in in MS Excel helped to solve the task of optimizing the grain drying time at W_f = 14 %. Figure 7 provides graphical representation of the calculation results.

For example, drying the grain with the initial moisture content W_f = 20% requires t_1 = 39 min and t_2 = 60 min at a vacuum value of 80 kPa and t_1 = 58 min at a vacuum value of 70 kPa. Drying the grain with the initial moisture content W_i = 16% requires t_1 = 0 to achieve W_f = = 14% and t_2 = 54 min at a vacuum value of 80 kPa.

In terms of energy the optimum drying mode corresponds to the minimum energy consumption of the drying machine (kWh) ensuring the specified final moisture content of the grain W_f:

$$E = [N_{tr}t_{tr} + N\left(t_{w1} + t_{w2} + k_{t1}t_{r2} + k_{t2}t_{r2}\right) + N_{vp}t_2 + N_b t_b / 60 \rightarrow \min \quad (4)$$

Where:

N_{tr} = Power of the feeder, 2.2 kW

N = total power of infrared transmitters, 6 kW

t_{w1}, t_{r1}, t_{w2}, t_{r2} = Time of grain heating up to T_{max} and periodic infrared transmitter operation for drying periods t_1 and t_2 min, respectively

k_{t1}, k_{t2} = Time periods of infrared transmitter operation in a periodic mode for drying periods t_1 and t_2, respectively

N_{vp} = Power to drive the vacuum pump (kW)

N_b = Fan power, 1.5 kW

If the grain reached the temperature T_{max} in the first period at a sufficiently high t_1 in time t_{w1} infrared transmitters operate at full power N in this time period and they operate in a periodic mode during the time (t_1-t_{w1}) and in the second period t_2. If the grain reaches the temperature T_{max} only in the second period Fig. 3 then the length of the periodic mode will be (t_1-t_{w1}). If the grain temperature does not reach T_{max} in the second period then $t_{r1} = t_{r2} = 0$. Note that time $t_1 = 0$ in some experiments (Table 3).

During the main experiment, grain heating time up to T_{max} 70°C (thermostat actuation time) and grain temperature at the end of the period when it didn't reach 70°C were additionally recorded in each trial. The following regression equation was obtained after statistical data processing:

$$t_w = -10.02+0.74T+0.1925P-0.0115W_iP-0.000983P^2; R = 0.952 \quad (5)$$

Where:

T = The temperature of grain heating during the full power operation of infrared transmitters (°C)

P = The absolute pressure in the drying chamber (kPa) which is related to the atmospheric pressure and the vacuum value $P = P_a - H$

To determine the part of infrared transmitter operating time in a periodic mode an additional experiment was performed. It recorded operation and interruption time of the infrared transmitters. Due to statistical experimental data handling we had the regression Eq. 6:

$$k_t = -0.8323+0.1177W_i+0.00189H-0.001984W_i^2; R = 0.990 \quad (6)$$

Optimal modes of barley grain drying were developed using the Eq. 4, taking into account Eq. 5 and 6. Table 4 shows the optimal modes for drying the grain to the final moisture content value of 14%.

Table 4: Optimal modes of drying barley in a vacuum infrared dryer

W_i (%)	H (kPa)	t_1 (min)	t_2 (min)	E (kW•h)
20	80	38.8	60.0	9.74
19	80	35.2	60.0	9.24
18	80	27.3	60.0	8.42
17	80	13.1	60.0	7.11
16	80	0.0	54.2	5.54
15	80	0.0	38.0	4.26

The drying modes given in Table 4 are identical to the modes found based on the maximum average grain drying speed. The reasons are as follows. Since, infrared radiation is the bulk of the energy consumption shorter heating time leads to a decrease in total energy required.

The optimal mode of drying barley from 20-14% moisture in the vacuum infrared drying machine for seed production and brewing implies specific energy consumption of 3.14 MJ/1 kg of evaporated moisture which is 1.4 times lower than in the contact convective type drying machine and 1.8 times lower than in convective type dryers (Anonymous, 2008; Sorochinsky, 2011). Vacuum value H has a direct effect on specific heat required for moisture evaporation in the designed vacuum infrared dryer. Lower vacuum values of up to 50 kPa increase specific energy consumption up to 4.5 MJ/1 kg of evaporated moisture. This is accounted for by the fact that vacuum lowers moisture evaporation temperature. Similarly, vacuum increases pressure gradient and drying speed (Ginzburg, 1960; Bettega *et al*., 2014; Byshov *et al*., 2016).

The average speed of drying barley seeds from 20-14% moisture content is 0.056%/min. Drying seeds of lower initial moisture implies lower average drying speed and the speed is 0.042%/min at $W_i = 18\%$ it is 0.022 %/min at $W_i = 15\%$ (Ginzburg, 1960; Lykov, 1968; Sutyagin *et al*., 2017). The results are fully in line with the existing studies on drying grain crops (Atanasevich, 1989; Baum and Rezchikov, 1983; Lebedev, 1962).

CONCLUSION

The regression dependence of the barley seed germination on the maximum heating temperature of the IR-transmitter surface is established. It is found that the heating time from 5-30 min and the initial grain moisture content in the 16-22% range do not have a significant effect on the thermal stability of barley seeds. It is proved that the highest possible temperature of barley seed heating that doesn't result in protein denaturation is 70°C.

The mode of grain drying in the vacuum infrared drying machine features the following parameters: maximum grain heating temperature, grain heating time in and without vacuum, vacuum value.

The regression dependence of the moisture removal on the mode parameters of drying barley seeds with different moisture content allowed us to study the drying processes in the vacuum infrared drying machine.

The mathematical models designed to optimize the barley drying operation modes made it possible to determine the minimum specific energy consumption and time of barley grain drying.

ACKNOWLEDGEMENT

The study was conducted under the grant of Republic of Bashkortostan based on the results of scientific research competition among young scientists and young scientist teams. The developed vacuum infrared machine for drying grain and crop seeds was presented at the 28th international specialized exhibition “Agrocomplex” (held in Ufa) and awarded a diploma and a gold medal.

REFERENCES

Adler, Y.P., 1976. [Planning an Experiment when Searching for Optimal Conditions]. 2nd Edn., Nauka Publisher, Moscow, Russia, Pages: 279 (In Russian).

Anonymous, 2008. [GOST 28293-89: Mine grain dryers; Power consumption]. Standartinform Publ., Moscow, Russia. (In Russian) https://translate.google.com/translate?hl=en&sl=ru&u=http://internet-law.ru/gosts/gost/3019/&prev=search

Anonymous, 2011. GOST 12038-84: Crop seeds; Methods for determining germination. USSR State Standard, Moscow, Russia. (In Russian) https://translate.google.com/translate?hl=en&sl=ru&u=http://stroysvoimirukami.ru/gost-12038-84/&prev=search

Atanasevich, V.I., 1989. [Drying Grain]. Agropromizdat Publisher, Moscow, Russian, Pages: 240 (In Russian).

Baum, A.E. and V.A. Rezchikov, 1983. [Drying Grain]. Kolos Publisher, Moscow, Russian, Pages: 222 (In Russian).

Bettega, R., J.G. Rosa, R.G. Correa and J.T. Freire, 2014. Comparison of carrot (Daucus carota) drying in microwave and in vacuum microwave. Braz. J. Chem. Eng., 31: 403-412.

Byshov, D.N., D.E. Kashirin, S.N. Gobelev, S.S. Morozov and A.V. Protasov, 2016. [To the issue of vacuum infrared drying of pollen (In Russian)]. Bull. Ryazan State Agrotechnological Univ. PA. Kostycheva, 29: 56-59.

Darvishi, H., M.H. Khoshtaghaza, G. Najafi and M. Zarein, 2013. Characteristics of sunflower seed drying and microwave energy consumption. Intl. Agrophys., 27: 127-132.

Faizrakhmanov, S.F., 2015. [Development of a microwave conveyor installation for drying sunflower seeds with the justification of its parameters and operating modes]. Ph.D Thesis, Department of Theoretical and Applied Mechanics, Bashkir State Agrarian University, Ufa, Russia. (In Russian)

Friesen, A.P., R.L. Conner, D.E. Robinson, W.R. Barton and C.L. Gillard, 2014. Effect of microwave radiation on dry bean seed infected with Colletotrichum lindemuthianum with and without the use of chemical seed treatment. Can. J. Plant Sci., 94: 1373-1384.

Ganeev, I.R., 2011. [Improving the efficiency of drying rapeseed with the use of electromagnetic radiation]. Ph.D Thesis, Bashkir State Agrarian University, Ufa, Russia. (In Russian)

Ginzburg, A.S., 1960. [Drying Food: A Tutorial]. Pishchepromizdat Publisher, Moscow, Russia, Pages: 683 (In Russian).

Ivanovich, K.V., P.A. Aleksandrovich, K.G. Vladimirovna and S.S. Alekseevich, 2013. [Heat Treatment of Grain in Installations of the Contact Type: Monograph]. Scientific Magazine Kontsept, Moscow, Russia, ISBN:9785905970221, Pages: 290 (In Russian).

Jokiniemi, T., T. Oksanen and J. Ahokas, 2015. Continuous airflow rate control in a recirculating batch grain dryer. Agron. Res., 13: 89-94.

Karimov, K.T., I.R. Ganeev, I.H. Masalimov, V.N. Permyakov and S.F. Fayzrakhmanov, 2016. [Device for drying and sorting bulk material]. Ramber TOP, Russia. (In Russian) https://translate.google.com/translate?hl=en&sl=ru&u=http://www.findpatent.ru/patent/257/2577909.html&prev=search

Lebedev, P.D., 1962. [Calculation and Design of Drying Units]. Gosenergoizdat Publisher, Moscow, Russia, Pages: 321 (In Russian).

Li, S., S. Cao and W. Meng, 2017. Design of grain dryers control system. Mater. Sci. Eng., 212: 1-9.

Li, Y., T. Zhang, C. Wu and C. Zhang, 2014. Intermittent microwave drying of wheat (Triticum aestivum L.) seeds. J. Exp. Biol. Agric. Sci., 2: 32-36.

Lykov, A.V., 1968. [Theory of Drying: Textbook]. Energy Publisher, Moscow, Russia, Pages: 472 (In Russian).

Maier, D.E., 2017. Grain Drying, Handling and Storage Handbook. MidWest Plan Service, Iowa State University, Ames, Iowa, ISBN:9780893731106, Pages: 150.

Manikantan, M.R., P. Barnwal and R.K. Goyal, 2014. Drying characteristics of paddy in an integrated dryer. J. Food Sci. Technol., 51: 813-819.

Martynov, V.M., 2018. [Optimization of Technological Processes of Public Catering: Textbook]. Bashkir State University, Ufa, Russia, Pages: 137 (In Russian).

Masalimov, I.K. and K.T. Karimov, 2014. Evaluation of methods for drying barley seeds. Bull. Rask, 3: 71-72.

Moreno, A.H., R. Hernandez and I. Ballesteros, 2017. Microwave drying of seeds of agricultural interest for Ecuador. Ampere Newsl., 1: 28-32.

Pinchuk, S.I., 2008. [Organization of the Experiment in Modeling and Optimization of Technical Systems: Tutorial]. Limited Liability Company, Dnepropetrovsk, Ukraine, Pages: 248 (In Russian).

Rogov, I.A., 1988. [Electrophysical Methods of Food Processing]. Agropromizdat Publisher, Moscow, Russia, Pages: 272 (In Russian).

Semenov, S.M., 2012. [Methods for Assessing the Effects of Climate Change on Physical and Biological Systems: A Textbook]. Roshydromet Publisher, Moscow, Russia, Pages: 511 (In Russian).

Soares, M.A.B., L.M.D.M. Jorge and F.D. Montanuci, 2016. Drying kinetics of barley grains and effects on the germination index. Food Sci. Technol., 36: 638-645.

Sorochinsky, V., 2011. [Decrease in fuel consumption in direct-flow grain dryers (In Russian)]. Feed, 7: 51-52.

Sutyagin, S.A., V.I. Kurdyumov, A.A. Pavlushin and V.I. Dolgov, 2017. [Reduction of the specific energy consumption for grain drying in a contact-type drying unit (In Russian)]. Bull. Samara State Agric. Acad., 2: 39-45.

Zhao, Y., Y. Jiang, B. Zheng, W. Zhuang and Y. Zheng *et al*., 2017. Influence of microwave vacuum drying on glass transition temperature, gelatinization temperature, physical and chemical qualities of Lotus seeds. Food Chem., 228: 167-176.

Zhidko, V.I., V.A. Rezchikov and V.S. Ukolov, 1982. [Grain Drying and Grain Dryers: A Textbook]. Kolos Publisher, Moscow, Russia, Pages: 239.