

Modelling of moisture loss from legumes in case of infrared radiation

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Summary

The article presents the experimental results and considers the models of dehydration of beans of “Tsanava” and “Red Field” varieties together with white lupine of “Dega” variety in infrared flux. The heating time, surface temperature and the initial moisture content of beans were used as independent variables. These parameters affect significantly the final moisture content of product and can be easily controlled in the technological process. The height of radiators above the product was viewed as a fixed parameter that leads to changes in ambient temperature and radiant flux density on the surface. The models of dehydration were based on simplified solutions of the system of heat and mass transfer differential equations. Two versions of the model were considered as follows: the dependence of the final moisture content on its initial value and the heating time; the dependence of the final moisture content on its initial value and the heating temperature. Analysis of the obtained coefficients showed that in the models discussed, it was possible to select only one of these coefficients. After determining the coefficients of the model from the results of the experiment, the expected prediction precision of the final moisture content in bean was to accuracy of approximately 2 %.

Keywords

infrared radiation; heat treatment; beans; moisture loss; mathematical modelling

Heat treatment, in particular with the use of radiation (infrared) energy supply, is an operation that is common in the technology of processing of grain. This method is used most frequently by small enterprises producing instant cereals and cereal flakes and is known as high-temperature micronization (HTM). Grain processing by this method was investigated in our earlier study [1].

The temperature and the final moisture content of grain during heating by infrared (IR) radiation are dependent on a number of factors, such as heating time, initial moisture content of grain and heat treatment conditions (irradiance and the temperature in the working medium). Typically, in industrial facilities, processing conditions depend on the design of the IR heating unit and

they rarely change during operation, even if such a possibility exists. The product's outlet temperature is regulated by its residence time in the working medium. Usually, the heating process is carried out in a thermal head at a large temperature difference and is limited by the darkening starting time on the grain surface. The product's temperature is constantly changing throughout the entire processing period, that is, the process is essentially non-isothermal.

The use of electromagnetic radiation for heating and heat treatment of products is based on the phenomenon of the absorption of radiation incident on the product and conversion of its energy into heat [2]. Unlike electromagnetic radiation, the heat treatment of product during infrared ra-

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diation is carried out not only by the method of convection heating, but also by the method of radiation heating.

In the manufacture of products from legumes, it is economically feasible to use the heat-treated full-fat soybeans in livestock feeding. It appeared to be certain that it is difficult to reduce the cost of these products in other ways [3]. The heat treatment not only increases the value of products, but also improves their effective use in feeding.

During the heating process, the product is dehydrated. The moisture content of source raw materials depends on their state in supplying, storage conditions and it may vary sometimes quite widely. The process of moisture loss by grains of a number of cereals and oil-bearing crops during IR heating was considered previously [4, 5]. However, those studies examined the objects, the physical dimensions of which were comparable to the penetration depth of IR radiation. In this case, a methodology was applied where the average temperature of the sample was assessed using a digital thermometer. When drying fruits and vegetables using various drying methods, such as infrared drying, infrared hot air drying, infrared vacuum, infrared pseudo-fluidized layer or infrared microwave drying, the effect of IR drying on drying time, effective moisture diffusion coefficient and textural as well as quality characteristics of dried apples, quince, grapefruit, lemon, persimmon, banana, peach, mushroom, carrot, pumpkin, garlic and onion were studied. IR heating has many advantages, including the high heat transfer rates, uniform heating, short processing times, high efficiency (80–90 %), low energy consumption, low energy costs and the improved final product's structure, porosity and quality [6]. IR methods can be used as an alternative to the existing drying and blanching methods for the production of high quality dried fruits and vegetables [6].

To study the effect of micronization at various moisture levels on the chemical and rheological properties of wheat, a series of tests were performed on samples of four wheat varieties (AC Karma, AC Barrie, Glenlea and Kanata) [7]. After exposure to IR radiation at three moisture levels (12 %, 16 % and 22 %), the seeds were ground to produce a straight flour. The protein fractionation test revealed a significant decrease in both monomeric proteins (from 54 % of total protein in the control to 37 % in a tempered micronized sample) and soluble glutenins (9.4–2.5 %). A strong negative correlation ($r = -0.98$) was found between the percentage of monomeric proteins and insoluble glutenins. The total extractable amount of protein in micronized samples brought

up to a moisture content of 22 % was reduced by 43.5 % compared to non-micronized controls, as determined using gel filtration HPLC (SE-HPLC).

Micronization had a significant effect on the properties of gluten, which could be seen from a decrease in water absorption ($P \leq 0.01$) and the setting time of the dough ($P \leq 0.01$). The results showed that micronization at 100 ± 5 °C had a detrimental effect on the gluten functionality of wheat flour, including a decrease in protein solubility and impairment of rheological properties. These phenomena can be associated with the formation of both hydrophobic interactions and disulfide bonds in wheat during micronization [7].

SALEHI and KASHANINEJAD [8] studied the effect of combined IR-vacuum drying on kinetics of drying, moisture diffusion coefficient, change in the surface (shrinkage) and kinetics of colour change of lemon slices. The authors found that wattage of the IR lamp and the vacuum pressure affected the drying time of lemon slices. The regression results showed that a quadratic model satisfactorily described the process of drying with a maximum R value and a minimum SE value. With an increase in wattage of the IR lamp from 300 W to 400 W, the effective diffusion coefficient of moisture increased from $2.92 \times 10^{-10} \text{ m}^2 \cdot \text{s}^{-1}$ to $1.58 \times 10^{-9} \text{ m}^2 \cdot \text{s}^{-1}$. The colour parameters L^* (luminance), a^* (redness/green), b^* (yellow/blue) and ΔE (total colour difference) were used to evaluate colour changes during drying [8].

ZVEREV and ZVEREVA [9] considered the method of high-temperature micronization (HTM) with heating in an IR stream of grain products to obtain functional food products with an extended shelf-life. The results of the analysis of the content of B and E vitamins showed that the IR treatment in the used mode only insignificantly affected their content in the studied flakes in comparison with the original raw material. After the heat treatment, the content of vitamin B1 decreased from 0.36 mg to 0.34 mg per 100 g of wheat, the content of vitamin B2 decreased from 0.11 mg to 0.10 mg per 100 g of wheat and the content of vitamin PP decreased from 6.22 mg to 6.20 mg per 100 g of wheat. The shelf-life was extended to 6 months [9, 10].

During the IR heat treatment, for a certain period of time, the temperature rises from the initial one to close to or greater than 100 °C. This would obviously lead to devitalization of the majority of microflora, the content of dextrins at a moisture content of 13.5 % for barley increased from 0.5 % to 22.5 %, while for wheat, at a moisture content of 12.7 %, it increased from 0.5 % to 11 %. External infestation for barley decreased from 1.0

to 0.083 and further to 0.0, while for wheat, it decreased from 1.0 to 0.11 and further to 0.0; internal infestation for barley decreased from 1.0 to 0.40 and further to 0.05, while for wheat it decreased from 1.0 to 0.35 and further to 0.04 [10].

At a supply flux of IR radiation with a density of $16 \text{ kW}\cdot\text{m}^{-2}$, the microflora of barley and wheat bacteria with an initial moisture content of 13.6 % decreased from 1.0 to 0.125 relative units, and fungi from 1.0 to 0.33 relative units, at a supply flux of IR radiation with a density of $20 \text{ kW}\cdot\text{m}^{-2}$, bacteria and mushrooms decreased to 0.0 relative units. This leads to an increase of the shelf life of products up to 6 months or more [10].

Based on a review of the literature and analysis of the problem being solved, we have developed area and determined the purpose of the research. The aim of the studies described in this article were as follows:

- Experimental study of the process of heating and moisture loss of some legumes with changes in the initial moisture content, irradiation and temperature of the working environment during high-temperature micronization (heating in IR radiation flux).
- Development of a specific mathematical model of moisture loss in legumes, based on the general theory of heat and mass transfer, occurring at a moisture content lower than hygroscopic, as well as identification of their coefficients based on the experimental data obtained. A mathematical model will allow us to investigate the process of dehydration of other legumes.

Based on the results of the study, as well as on existing experience in the IR heat treatment of cereal crops (barley, rye and others), the experimental results on IR dehydration of beans would be obtained for the first time. The mathematical models of dehydration have been proposed and their coefficients have been assessed.

Scientific hypothesis

Moisture loss is a thermally activated process, so the final moisture content of product can pri-

marily be determined by the heating time and the product temperature. Since these variables are interdependent under IR heating conditions, the mathematical model of dehydration can be expressed either in terms of time or in terms of temperature. We also assume that the stationary heat treatment conditions, initial humidity, namely, illumination and temperature of the working environment, will also have an effect.

MATERIALS AND METHODS

Samples

Research covered the varieties of bean such as “Tsanava” variety (Gori, Gori region, Georgia), “field red” bean (Tskhaltubo, Tskhaltubo region, Georgia) and the so-called “white lupine” (Khoni, Khoni region, Georgia) of harvest in 2019. These products were purchased from the market. Geometrical characteristics of the grain are shown in Tab. 1.

Equipment

For experiments on heat treatment of beans, a QP1 model (Elcer, Odesa, Ukraine) of a panel for the halogen quartz emitters (the panel composed of 7 emitters) was used as a source of IR radiation. The dimensions of a panel for the quartz emitter were $247 \text{ mm} \times 62 \text{ mm}$. The length of the tube was 245 mm, tube step was 8.55 mm, rated power was 1 kW and emitter temperature was $750\text{--}800^\circ\text{C}$. The diagram of the test bench of the heat treatment by the panel of infrared rays is shown in Fig. 1.

The linear dimensions of beans were determined using an electronic digital caliper VINCA DCLA-0605, 150 mm. (Neiko Tools, Lu Chu Hsiang, Taiwan). The surface temperature of the beans sample was measured under the middle lamp of the emitter, being determined as follows: beans were placed on the pallet in a monolayer that, for a fixed amount of time (30, 60, 90 or 120 s), was placed in a heated IR-treatment zone. Then, the pallet was quickly removed and the temperature of beans was determined using an AR360A+ infrared laser thermometer (Sim-

Tab. 1. Geometrical characteristics of grains.

Variety of beans	Geometrical parameters			Weight of one bean [g]	Density of stacking monolayer [$\text{g}\cdot\text{sm}^{-2}$]
	Length [mm]	Width [mm]	Thickness [mm]		
“Tsanava”	15.4 ± 2.7	8.5 ± 0.4	6.0 ± 0.8	0.61 ± 0.01	0.8
“Field red”	12.8 ± 1.2	8.2 ± 0.5	5.5 ± 0.4	0.31 ± 0.01	0.5
White lupine “Dega”	18.7 ± 3.4	13.2 ± 1.2	6.6 ± 0.8	1.02 ± 0.02	0.4

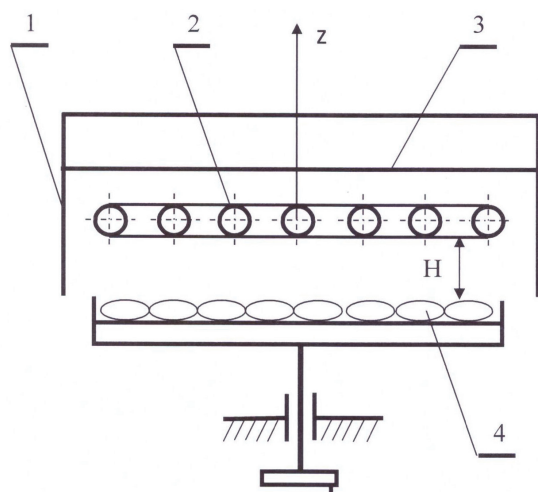


Fig. 1. The test bench diagram.

Scheme of measuring the temperature of the monolayer of beans: 1 – lateral reflective screens, 2 – block of emitters, 3 – upper reflective screen, 4 – monolayer of beans on a stage.

zo, Long, China). The temperature measurement interval varied from $-50\text{ }^{\circ}\text{C}$ to $+360\text{ }^{\circ}\text{C}$ and the temperature measurement error was $0.5\text{ }^{\circ}\text{C}$ due to heat loss, which could be taken as insignificant.

The initial moisture content of beans was determined using an electronic digital meter of grain and seed moisture (moisture meter) VSP-100 (PAtools, Kharkiv, Ukraine). Additionally, moisture loss during the IR heating was estimated as the difference between the initial sample weight and its weight after the heat treatment. The sample weight of grain before and after the heat treatment was determined using an electronic digital analytical balance SF-400C model (Toms, Qilin, China) with a weighing accuracy of 0.01 g . The moisture content (W) after the heat treatment was calculated based on the initial moisture content (W_0) and mass loss (Δm) according to the formula based on the standards GOST 13586.5-2015 [11] and ISO 1446:2018 [12].

$$W = \frac{100 \times \left(\frac{W_0}{100} - \frac{\Delta m}{m_0} \right)}{\left(1 - \frac{\Delta m}{m_0} \right)} \quad (1)$$

where W_0 is expressed in percent; m_0 is an initial sample weight (in grams) and Δm is sample weight loss (in grams).

The independent variables were as follows: initial moisture content (W_0), exposure heat treatment time (t), and the height of the emitters above the monolayer of grain (H). The W_0 value varied in the range of 10–35 % and had no strictly fixed levels. The exposure time changed to an

upper level of 120 s at a step of 30 s. The height had three levels – 50 mm, 75 mm or 100 mm. The grain's temperature (T) after the heat treatment was used as a generic variable.

Statistical analysis

Non-linear modelling was carried out by using a software application suite „STADIA-6“ [13]. Measuring the adequacy of the models is a complicated procedure requiring high computational burden, which is rapidly growing along with the dimensions of space of the external parameters. By volume, this task may greatly exceed the task of parametric optimization of a model itself (especially in the case of a non-linear model). Therefore, it may not be resolved for newly-designed objects. Some indication of the adequacy of the models is provided by the squared multiple correlations (R^2) and residual statistical deviation (F). To describe the set of variate values, we used statistical functions of the average arithmetic value and the average standard error. The value of reliability was set at $p < 0.05$.

RESULTS AND DISCUSSION

The method of high-temperature micronization (HTM) – heating in IR fluxes for heat treatment of food products and legumes can be used to obtain foods with a higher nutritional value [14]. A simple infrared system consists of an emitter, which is the heat source (IR lamp) and a reflector, which is used for temperature control. The efficiency of IR equipment mostly depends on the type of the heat source used. The emitter determines the colour of the light, the wavelength of the radiation process, the process temperature and the power density. Electric and gas heaters are commonly used for the process of heating [15]. The principle of application and comparative performance of IR energy for drying a range of food materials, including grains, fruits, vegetables and seafood, has been critically discussed in the recent past. The effects of process variables on energy consumption, drying time, rate of drying and quality of the dried product were explained in detail [16].

Post-harvest processing of dry beans is necessary to ensure high-quality cooking, storage and food safety [17]. IR methods can be used as an alternative to the existing drying and blanching methods to produce high quality dried fruits and vegetables. Suitable mathematical models for simulating infrared drying of various fruits and vegetables were previously summarized, and recommendations for use by manufacturers of this

method and model in the production of dried fruits and vegetables were provided [6]. However, the proposed mathematical models are not suitable for achieving the goal of the present study, since drying of fruits and vegetables proceeds at a moisture level higher than the hygroscopic one, and high-temperature micronization of legumes, at a moisture content of $30 \pm 5\%$ and short times, lead to changes in their biochemical properties and nutritional value.

When using combined IR-vacuum drying of lemon slices, an increase in the power of IR radiation negatively affected colour intensity ΔE . Various kinetic models were used to fit the experimental data [8]. The results showed that the power model was most suitable for describing the intensity of colour change (ΔE). The proposed kinetic models are not suitable for solving the problems of the present study, since they describe the process of moisture loss above hygroscopic moisture. The same conclusion was reached by analysis of further literature, which discusses drying of fruits and vegetables.

When micronizing cereals or legumes with a moisture content of $30 \pm 5\%$, some beneficial changes are observed, such as partial gelatinization of starch or inactivation of enzymes that are responsible for degradation and denaturation of anti-nutritional compounds. Partial gelatinization due to micronization improves starch digestibility and palatability, and shortens cooking time without significantly affecting other nutrients present in the beans [4]. During high-temperature micronization, the height of the emitters above the pan determines the irradiance of the monolayer of beans, and the temperature of this working medium. Fig. 2 illustrates the experimental data of the dependency of the moisture content on its initial value and the height of the emitter at a fixed exposure of 90 s. If approximate results were obtained in the form of exponential functions at 90 s and 60 s, then formulas for determination of the final moisture content of beans could be obtained (Tab. 2). It can be seen from the obtained expressions that the effect of the distance from the emitter to the monolayer of beans H on the final moisture content W is very weak, and the

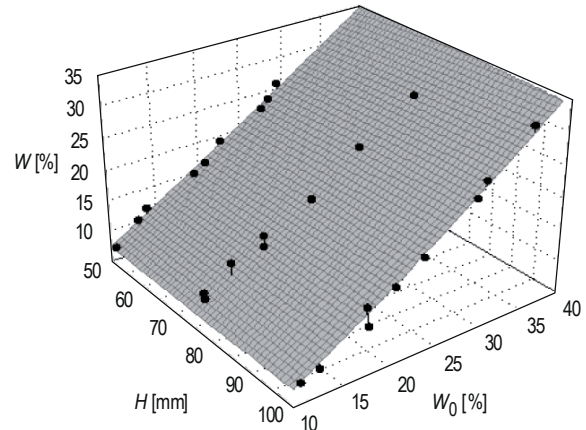


Fig. 2. Dependency of the final moisture content of beans on its initial value at an exposure of 90 s.

W – final moisture content, W_0 – initial moisture content, H – height of emitters panel.

dependency on the initial moisture content W_0 is close to linear. Typical dependencies of the final moisture content on an exposure at various initial moisture values are shown in Fig. 3. Fig. 4 shows the empirical dependencies of the final moisture content on its initial value at the different exposures (the height of the emitter varied in the range of 50–100 mm). Fig. 3 and Fig. 4 illustrate that for all exposure levels the dependencies of the final moisture content on the initial moisture content was close to linear, and, as expected, with an increasing exposure, the final moisture content decreased.

Based on works on the theory of unsteady fields of the molar-molecular mass transfer potential in order to estimate the moisture content W depending on the initial moisture content and the grain's temperature during IR heating, Eq. 4 was proposed as a mathematical model [18, 19]:

$$W = W_0 \times \left(1 - \frac{\Delta T}{A}\right)^B \quad (4)$$

where ΔT is temperature increment (in degrees celsius), A and B are empirical constants (dimensionless).

Tab. 2. Equations of the final moisture content.

Parameter	Equation	t [s]	F [mm]	R^2	Number of equation
W [%]	$W_1 = 0.43 H^{0.069} W_0^{1.11}$	90	0.94	0.98	Eq. 2
W [%]	$W_2 = 0.63 H^{0.061} W_0^{1.03}$	60	0.98	0.98	Eq. 3

W – final moisture content, W_0 – initial moisture content (in percent), H – height of emitter above the grain monolayer (in millimetres), t – time of exposure to infrared irradiation, F – residual standard deviation, R^2 – square of the coefficient of multiple correlation.

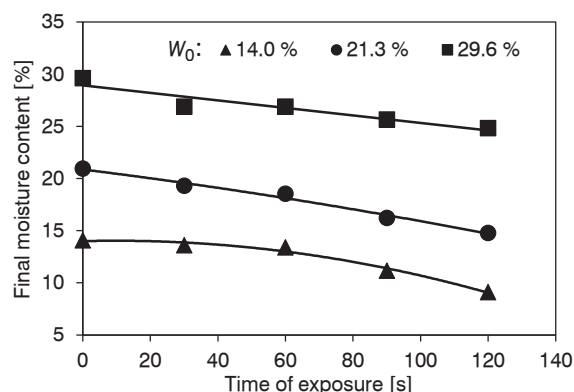


Fig. 3. Change in the moisture content of “Red Field” variety beans over exposure to infrared irradiation.

The distance from the emitter to the monolayer of grain H was 50 mm. Initial moisture content W_0 was 14.0 %, 21.3 % or 29.6 %. Individual points are average values from 5 measurements.

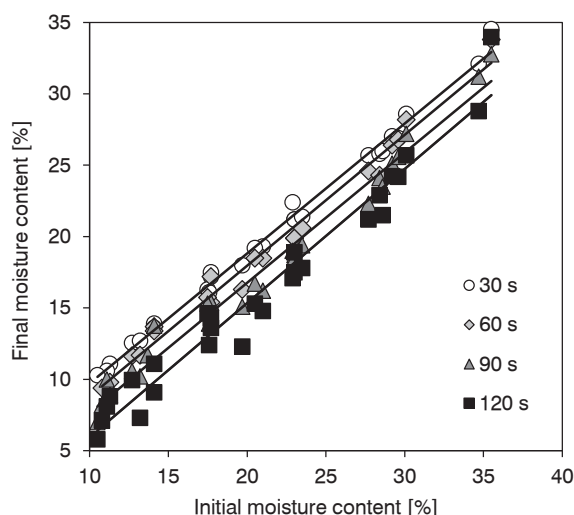


Fig. 4. Dependency of the final moisture content of beans on its initial value at different time of exposure to infrared irradiation.

Dependency equations for different exposure times:

30 s ($y = 0.9105x + 0.6074$; $R^2 = 0.99$),

60 s ($y = 0.8867x - 0.5544$; $R^2 = 0.97$),

90 s ($y = 0.8968x - 3.0923$; $R^2 = 0.95$),

120 s ($y = 0.8303x - 3.9759$; $R^2 = 0.88$).

Tab. 3 presents the results of identification of coefficients of Eq. 4 according to the experimental data for individual crops at the different heights of the emitter H . The values of the model coefficients substantially depend on the initial approximation, reflecting the set of the local minima of the cost function for optimizing the model coefficients. $A = 250$ and $B = 1$ were taken as the initial approximations. Tab. 3 shows that, for legume products under study, there was a slight dif-

ference in the coefficients of the model, therefore the model should be based on experimental data. Tab. 3 shows the Eq. 4 parameters at the different heights of the emitter above the monolayer of grain according to the combined experimental data on all kinds of grain, as well as for a generalized model, according to the results for all heights and kinds of grain. Fig. 5 illustrates the experimental and calculated data on the generic Eq. 4. Tab. 4 shows that, with an increase in the height of the emitter above the monolayer of product, coefficient A decreased. Probably, the statistics of the model can be slightly improved by introducing the height H into the generalized model as an additional variable.

Eq. 4 of the final moisture content on the final temperature, which was based on the dependencies [16] and on our earlier studies, was considered above

$$W = W_0 \exp(-At) \quad (5)$$

where t is the exposure heat treatment time (in seconds) and A is an empirical constant (dimensionless).

Tab. 5 presents the results of identifying the coefficients of Eq. 5 according to the experimental data for individual crops at various heights of the emitter above the monolayer of grain. Tab. 6 presents the parameters of Eq. 5 at different heights of the emitter above the monolayer of grain according to the combined experimental data for all kinds of grain and for the generalized model according to the results for all heights and kinds of grain. Fig. 6 illustrates the experimental and calculated data on the generic Eq. 5.

Tab. 6 shows that, as in the previous case, with an increase in the height of the emitter above the monolayer of grain, the coefficient A decreased. Probably, the statistics of the model can be improved by introducing the height H as an additional variable into the generalized model. However, the number of coefficients to be identified would increase in that case.

Based on the accepted theory, a program for calculating the basic quantities was designed using a mathematical package MathCad (Mathsoft, Cambridge, Massachusetts, USA) [20].

CONCLUSIONS

The proposed models of dehydration of beans and lupine during the combined convective and radiation (radiant) heating are based on the theoretical concepts [18]. After identifying the coefficients, the models allow us to predict the

Tab. 3. Parameters of Eq. 4 for individual kinds of beans.

Bean variety	H [mm]	A	B	F [mm]	R^2
"Tsanava"	50	455	1.03	0.99	0.98
	75	503	1.02	0.54	0.99
	100	626	0.98	1.01	0.98
"Field red"	50	674	1.02	1.16	0.97
	75	502	1.02	0.54	0.99
	100	626	0.98	1.01	0.98
White lupine "Dega"	50	672	1.02	1.33	0.97
	75	591	1.00	1.12	0.99
	100	402	1.02	0.81	0.98

H – distance of the emitter from the monolayer of beans, A – empirical constant, B – empirical constant, F – residual standard deviation, R^2 – square of the coefficient of multiple correlation.

Tab. 5. Parameters of Eq. 5 for individual kinds of beans

Bean variety	H [mm]	A	F [mm]	R^2
"Tsanava"	50	0.00275	0.94	0.98
	75	0.00217	0.71	0.98
	100	0.00228	1.38	0.96
"Field red"	50	0.00216	1.00	0.98
	75	0.00192	0.70	0.98
	100	0.00101	0.99	0.98
White lupine "Dega"	50	0.00245	0.92	0.98
	75	0.00185	1.24	0.98
	100	0.00236	0.41	0.99

H – distance of the emitter from the monolayer of beans, A – empirical constant, F – residual standard deviation, R^2 – square of the coefficient of multiple correlation.

Tab. 4. Parameters of Eq. 4 generalized for all kinds of beans.

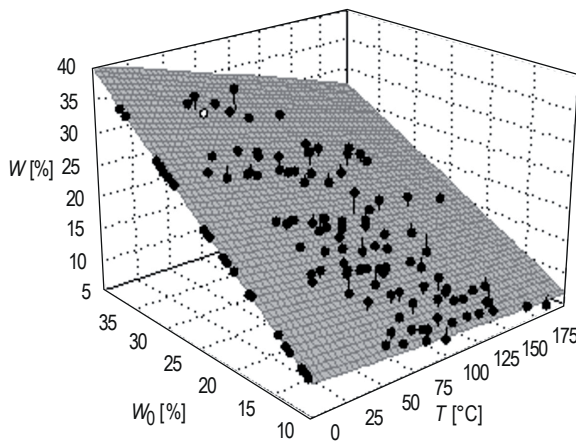
H [mm]	A	B	F [mm]	R^2
50	629	1.01	1.31	0.96
75	609	1.00	0.88	0.98
100	585	1.00	1.18	0.98
Generalized model	630	1.00	1.13	0.97

H – distance of the emitter from the monolayer of beans, A – empirical constant, B – empirical constant, F – residual standard deviation, R^2 – square of the coefficient of multiple correlation.

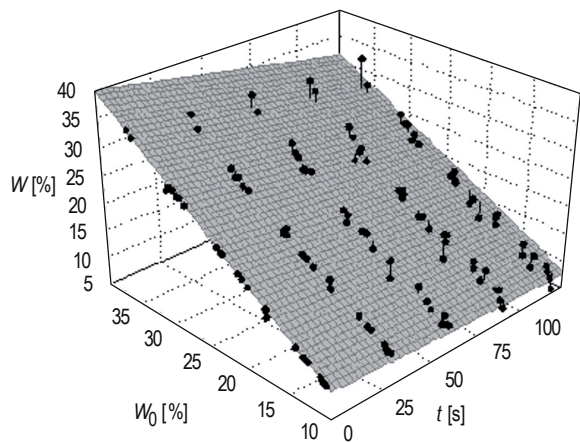
Tab. 6. Parameters of Eq. 5 generalized for all kinds of beans.

H [mm]	A	F [mm]	R^2
50	0.00244	0.98	0.98
75	0.00193	0.91	0.98
100	0.00164	1.37	0.97
Generalized model	0.00198	1.19	0.97

H – distance of the emitter from the monolayer of beans, A – empirical constant, F – residual standard deviation, R^2 – square of the coefficient of multiple correlation.


Fig. 5. Experimental data and data calculated by Eq. 4.

W – final moisture content, W_0 – initial moisture content, T – temperature.


Fig. 6. Experimental data and data calculated by Eq. 5.

W – final moisture content, W_0 – initial moisture content, t – time of exposure to infrared irradiation.

final moisture content of grain, at an accuracy of approximately 2 %, by controlling the residence time of the product in the processing zone or its outlet temperature.

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REFERENCES

- Zverev, S. – Sesikashvili, O.: Heating and dehydration of grain and cereals at a combined energy supply. *Potravinarstvo – Slovak Journal of Food Sciences*, 12, 2018, p. 79–90. DOI: 10.5219/840.
- Jones, P.L.: High frequency heating: In: *Thermopedia* [online]. Danbury : Begell House, 2 February 2011 [cited July 2021]. ISBN: 978-1-56700-456-4. DOI: 10.1615/AtoZ.h.high_frequency_heating.
- Shulaev, G. – Betin, A.: Mikronizirovannii soevie bobi v korme dlja molodikh svinei. (Micronized soybeans in young pig feed.) *Kombi-korma*, 2, 2010, pp. 76–80. ISSN: 0235-2605. In Russian.
- Deepa, C. – Hebbar, H. U.: Effect of high-temperature short-time micronization of grains on product quality and cooking characteristics. *Food Engineering Reviews*, 8, 2016, pp. 201–213. DOI: 10.1007/s12393-015-9132-0.
- Deepa, C. – Hebbar, H. U.: Effect of micronization of maize grains on shelf-life of flour. *Food Processing and Preservation*, 41, 2017, pp. 13–19. DOI: 10.1111/jfpp.13195.
- Salehi, F.: Recent applications and potential of infrared dryer systems for drying various agricultural products: A review. *International Journal of Fruit Science*, 20, 2020, pp. 586–602. DOI: 10.1080/15538362.2019.1616243.
- Sun, S. – Watts, B. M. – Lukow, O. M. – Arntfield, S. D.: Effects of micronization on protein and rheological properties of spring wheat. *Cereal Chemistry*, 83, 2006, pp. 340–347. DOI: 10.1094/CC-83-0340.
- Salehi, F. – Kashaninejad, M.: Modeling of moisture loss kinetics and color changes in the surface of lemon slice during the combined infrared-vacuum drying. *Information Processing in Agriculture*, 5, 2018, pp. 516–523. DOI: 10.1016/j.inpa.2018.05.006.
- Zverev, S. V. – Zvereva, N. S. (Ed.): *Funktsionalnie zernovie produkti. (Functional grain products.)* Moscow : DeLi Print Publishers, 2006. ISBN: 5-94343-106-3. In Russian.
- Zverev, S. V.: *Visokotemperaturnaia mikronizatsia v proizvodstve zernoproduktov. (High-temperature micronization in production of cereal products.)* Moscow : DeLi Print Publishers, 2009. ISBN: 978-5-94343-202-6. In Russian.
- GOST 13586.5-2015. Zerno. Metod opredelenia vlazhnosti (Grain. Moisture determination method (with amendments.) Moscow : Interstate Council for Standardization, Metrology and Certification, 2016. <<https://docs.cntd.ru/document/1200124082>> In Russian.
- ISO 1446:2018. Green coffee – Determination of the moisture content – Basic reference method. Geneva : International Organization for Standardization, 2018.
- Kulaychev, A. (Ed.): *Metodi i sredstva analiza dannikh v srede Windows Stadia-6. (Methods and tools of data analysis in a Windows environment STADIA-6.)* Moscow : Moscow State University M. V. Lomonosov, 1999. ISBN: 5-89-357-016-2. In Russian.
- Pan, Z. – Atungalu, G. G. – Grego, G. (Ed.): *Infrared heating for food and agricultural processing.* Boca Raton : CRC Press, 2010. ISBN: 9780429150876. DOI: 10.1201/9781420090994.
- Vaidyanathan, J. S. – Krishnamurthy, K.: Infrared heating for decontamination. *Food Science and Nutrition*, 8, 2013, ID 24398342. Online ISSN: 2048-7177.
- Sakare, P. – Prasad, N. – Thombare, N. – Singh, R. – Sharma, S. C.: Infrared drying of food materials. *Recent Advances, Food Engineering Reviews*, 12, 2020, pp. 381–398. DOI: <https://doi.org/10.1007/s12393-020-09237-w>.
- Campos-Vega, R. – Bassinello, P. Z. – Cardoso Santiago, R. A. – Oomah, B. D.: Dry beans: processing and nutritional effects. In: Grumezescu, A. M. (Ed.): *Therapeutic, probiotic, and unconventional foods.* Bucharest : Academic Press, 2018. ISBN: 9780128146262. DOI: 10.1016/B978-0-12-814625-5.00019-4.
- Lykov, A. V. – Mikhailov, Y. A. – Duncan, J. (Ed.): *Theory of heat and mass transfer.* Maryland : Institute for Physical Science and Technology, 1963. ISBN: 978-0706505610.
- Isaev, S. I. – Kozhinov I. A. – Leontiev A. I. (Ed.): *Teoria teplomassoobmena. (Heat and mass transfer theory.)* 3rd edition. Moscow : N. E. Bauman Moscow State Technical University, 2018. ISBN: 978-5-7038-4527-1. In Russian.
- Makarov, E. – Sergiyenko, Y. (Ed.): *Inzhinernie raschoti v Mathcad 15 (Engineering calculations in Mathcad 15.)* Moscow – St.Petersburg : Piter, 2011. ISBN: 978-5-459-00357-4. In Russian.

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