HEATING AND DEHYDRATION OF GRAIN AND CEREALS AT A COMBINED ENERGY SUPPLY

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ABSTRACT

The paper dwells on the development of experimental dependencies of heating and dehydration of grain and cereals when varying the irradiance, ambient temperature in the heat treatment zone and the initial moisture content of product, and the development of the mathematical models for heating and dehydration of some grains and cereals. The grain was heated on the laboratory equipment with quartz halogen linear infrared emitters. The irradiance on the working surface in the treatment zone was determined by calculation using a specially developed program. The ambient temperature was determined by a thermocouple thermometer placed in a ceramic tube. The grain temperature was estimated as average by weight by a thermocouple thermometer after its transfer into a thermally insulated container. The following dependencies have been obtained: 1 – Temperature dependence of the heating time for different heating modes and initial moisture content. 2 – Dependence of moisture content on the heating time under different conditions and initial moisture content. 3 – Dependence of moisture content on a temperature under different conditions and constant initial humidity. The models of the heat-moisture exchange and dehydration processes have been created, and the model parameters K_0 and K_T of the temperature dependence of some grains have been identified, as well as their dependence on moisture content and treatment modes has been evaluated. It has been established that this model describes adequately the process of dehydration to an extent limited by the upper temperature value of grain not much more than 100 ºC. Within not limited to the upper temperature value of grain not much more than 100 ºC. From the presented graphs (Figures 1.24 – 1.26) and earlier obtained results for barley and millet, it can be assumed that the model describes adequately experimental data on the small-sized (3 – 5 mm) objects.

Keywords: IR; radiation; grain; dehydration; heat

INTRODUCTION

Heat treatment, in particular, through the use of the radiative (infrared) energy supply, is an operation fairly common in the technological processes of processing food products, including grain. (**Pan and Atungalu, 2002; Zverev, 2009**). Heat transfer is carried out in two ways: by convective method from the air medium in the processing zone, and by radiation method (infrared radiation). It could therefore be spoken of a combined heat supply. Industrial installations based on this principle of heating are used in small and medium-sized grain processing enterprises in the processes of production of instant cereals, cereal flakes, feed ingredients, including for decontamination and inactivation of anti-nutrients. The heating process, as a rule, is carried out at a high thermal head and is limited to the time of the beginning of darkening of the grain surface. The temperature of product varies continuously throughout the processing period, that is, the process is of a substantially non-isothermal nature.

The change in temperature during the heating process is paralleled by dehydration of product. The temperature and final grain-moisture content of the in the process of heating by infrared (IR) radiation is determined by a number of factors: heating time, initial grain-moisture content, and heat treatment modes (irradiance, ambient temperature within the exposure zone). As a rule, in industrial installations the modes are conditioned by the design, and they rarely change during the operation, even if such an option is available. The moisture content of source raw material depends on its conditions on delivery, storage conditions and can vary, sometimes within rather wide limits. The outlet temperature of product is controlled by its residence time within the exposure zone. The heating process, as a rule, is carried out at a high thermal head and is limited to the time of the beginning of darkening of the grain surface. The temperature of product varies continuously throughout the treatment period, that is, the process is of a substantially non-isothermal nature.
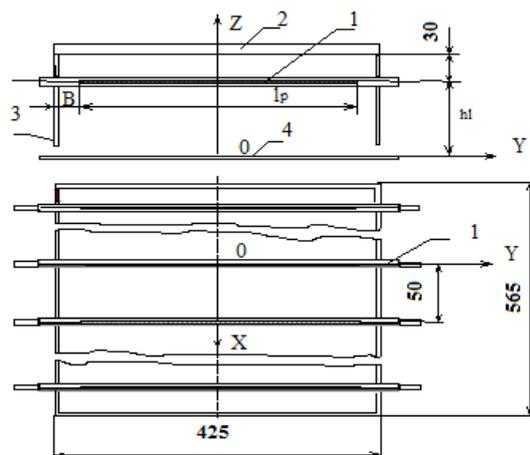
Figure 1 Diagram of the experimental-industrial block of the emitters: 1. The KGT-1000-220-type infrared source; 2 – Top reflector; 3 – Side reflector; 4 – A working surface of the processing zone.
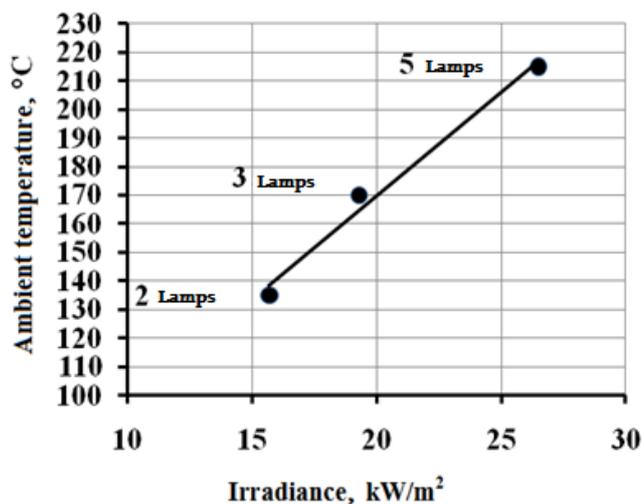

Figure 2 The dependency diagram of the ambient temperature in the treatment zone on the irradiance.

The work was aimed at obtaining the experimental dependencies and developing the models of heating and dehydration of grain (cereal) by varying irradiance, ambient temperature in the heat treatment zone of infrared heating of grain and cereals, and the initial moisture content of product.).

Scientific hypothesis

The temperature and final grain-moisture content of the in the process of heating by infrared (IR) radiation is determined by a number of factors: heating time, initial grain-moisture content, and heat treatment modes (irradiance, ambient temperature within the exposure zone). There is a correlation dependence of moisture content on the temperature of product, as well as influence of above listed factors on it. There is a probability of its invariable towards some of these factors.

MATERIAL AND METHODOLOGY

Heating of grain was carried out on the laboratory equipment with the KGT-1000-220-type quartz halogen linear infrared emitters.
Diagram of the equipment is shown in Figure 1.

The irradiance on the working surface in the processing zone was determined by calculation using a specially developed program. Variation by the number of the emitters, height of their installation above the monolayer of grain product and the type of pallet allowed changing independently, under a limited range, the irradiance and ambient temperature in the treatment zone. Change in the number of lamps, i.e. of the installed total power of the emitters in a fixed closed volume of the working area of the laboratory equipment leads to an increase in the ambient temperature. The dependency diagram of the irradiance and ambient temperature in the treatment zone when the lamps are installed at an altitude hl = 100 mm, is shown in Figure 2.

Grain was arranged in a monolayer on a pallet, which for a fixed time was placed in a heated treatment zone. Then it was poured into a thermally insulated container, where the average temperature of its mass was determined by using a thermocouple and an electronic thermometer.

As the subjects of research, there were used triticale (Triticosecale Wittmack) grain (the average thickness – 2.8 mm, the average weight of corn seed – 0.050 g), spelt (Triticum spelta) cereal (the average thickness – 2.1 mm, the average weight of corn seed – 0.031 g) and white

lupine (Lupinus albus) grain (the average thickness 4.4 mm, the average weight of corn seed – 0.23 g).

The significant factors influencing the rate of grain heating at a high-temperature micronization (HTM) are heat treatment modes (ambient temperature, irradiance on the surface of the monolayer) and moisture capacity of product. The experiment plans included the widest possible ranges of factors, however, for technical reasons, it had been impossible to cover the high irradiance region at a low ambient temperature.

The ambient temperature was determined by means of a thermocouple thermometer placed in a ceramic tube with a high reflection ratio in the infrared spectrum. The grain temperature was estimated as the average by weight by a thermocouple thermometer after its transfer into a thermally insulated container (reproducibility of the results was approximately ±3 °C), humidity - according to GOST (State Standard) 13586.5-2015 (Grain. Method for determination of moisture content).

Statisic analysis

Nonlinear modeling was carried out by using an application software package "STADIA-6", developed at the M.V. Lomonosov Moscow State University, (**Kulaychev, 1999**).

Scoping the adequacy of the models is a complex procedure, requiring high computational costs, which are rapidly growing with dimensions of space of external parameters. By the volume, this task may greatly exceed the task of parametric optimization of a model itself (especially in the case of a nonlinear model), that's why for the newly-designed objects, it may not be resolved. Some indication of the adequacy of the models is provided by the Squared multiple correlation, R2, (Table.1 and 2). In addition, directly in the diagrams in Figure 21 – 26, we can see that the residual dispersion and the dispersion medium differ considerably.

RESULTS AND DISCUSSION

The relationships between a temperature and a heat time at different heat modes and initial moisture content

Figures 3 – 5 illustrate the empirical relationships between a temperature increment of some types of grain and cereals and the time $\Delta T(t)$ at different heat modes.

It is obvious that with the intensification of heat supply (by increasing the ambient temperature and/or the irradiance or the emitter power), the heating rate is increasing, that is, the heat time to a fixed temperature is reduced.

The effect of the initial moisture content on the nature of the products temperature change can be seen in Figures 6 – 8.

With increasing moisture content for fixed heating times and modes, the temperature slightly reduces.

The relationship between a moisture content and a heat time at different heat modes and initial moisture content

Similar relationships for the relative loss of moisture $\Delta U(t) / U_0$ (relative to the initial moisture content) are shown in Figures 9 – 11. As can be seen, the rate of moisture loss depends heavily on the heat modes.

The relationship of a moisture content on a temperature at different heat modes and constant moisture content

Reconstruct the graphs of moisture loss into the functions of the temperature. The results are shown in Figures 12 – 14.

As can be seen, the relationships U(T) are practically invariant to heat modes, but they depend on the initial moisture content.

The morphology of the moisture content/temperature curves in the general case can be described as follows. At the initial stage of heating, a significant decrease in moisture content is observed, then the moisture content is decreasing, then it is diminishing by law close to linear, at
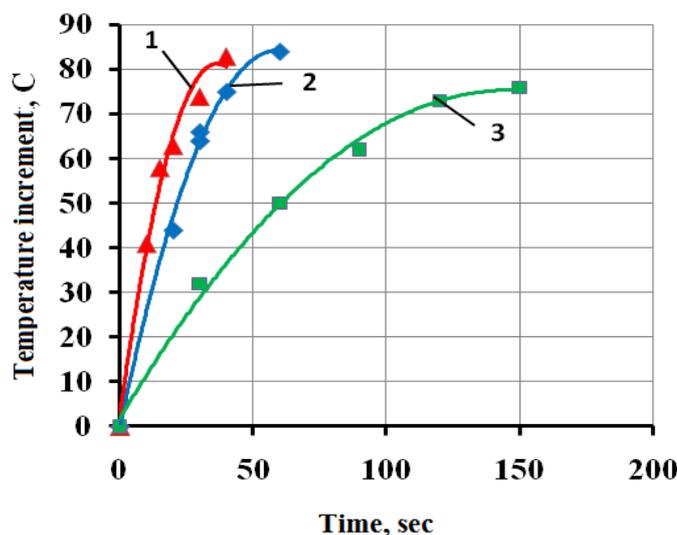
Figure 3 The relationship between a temperature increment of a RUNO-type spelt with initial moisture content of 18%, and a heat time at the different irradiance and ambient temperature T_c: 1 – E=23 kW.m^{-2}, T_c = 303 ºC; 2 – E = 11 kW.m^{-2}, T_c = 270 ºC; 3 – E = 0 kW.m^{-2}, T_c = 212 ºC.
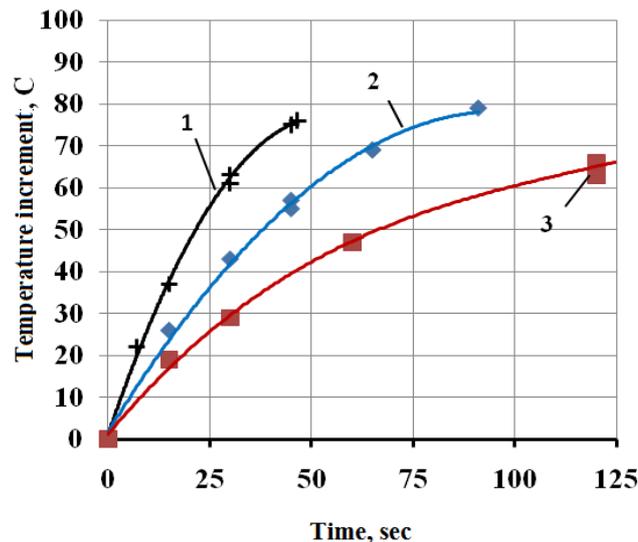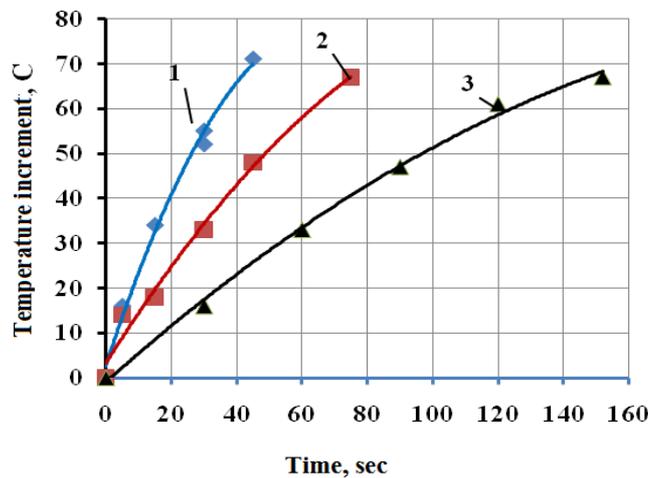
Figure 4 The relationship between a temperature increment of triticale and initial moisture content of 15%, with a heat time at the different irradiance and E ambient temperature T_c: 1 – E = 16 kW.m^{-2}, T_c = 271 ºC; 2 – E = 10 kW.m^{-2}, T_c = 204 ºC; 3 – E = 0 kW.m^{-2}, T_c = 148 ºC.

Figure 5 The relationship between a temperature increment of a DEGA-type white lupine with initial moisture content of 18%, and a heat time at the different irradiance and ambient temperature T_c: 1 – E = 22 kW.m^{-2}, T_c = 301 ºC; 2 – E = 13 kW.m^{-2}, T_c = 223 ºC; 3 – E = 0 kW.m^{-2}, T_c = 177 ºC.

the temperatures around 100 °C the rate of moisture loss increases again, and then decreases, falling to zero. The initial stage can be explained by the increased initial moisture content of the near-surface layers caused by the inadequate time of binning and by the non-aligned moisture content in the grain volume, or by the presence of a shell with different from kernel gyroscopic properties (for example, in lupine). The section near the temperature of 100 °C is associated with the intensification of evaporation near the critical point, and is due to the "burning out" of moisture. The nature of the dependence of a particular curve depends on product, initial moisture content, heat modes, the temperature range under consideration.

Modeling of the processes of heat-moisture exchange

There have been put forward many mathematical models. In general, the processes of heat and moisture exchange are interrelated and described by a system of corresponding nonlinear differential equations, which, as a rule, cannot be solved analytically. The application of numerical methods is also practically impossible, since the series of coefficients that are included in the equations are not defined. Therefore, we have to resort to various kinds of quite oversimplified assumptions and simplifications.

Let's use the solution obtained by A.V. Lykov in the form of exponential series (**Lykov and Mikhailov, 1963**).

$$Y = 1 + a_1 \exp(-K_1 t) + a_2 \exp(-K_2 t) + a_i \exp(-K_i t), \quad (1)$$

where
$Y = (T - T_0)/(T_\infty - T_0)$ – for the temperatures;
$Y = (U - U_0)/(U_\infty - U_0)$ – for moisture content;
T – temperature;
T_0 – wetting temperature;
T_∞ – temperature at t→∞;
U – moisture content;
U_0 – initial moisture content;
U_∞ – moisture content at t→∞;
t – time;

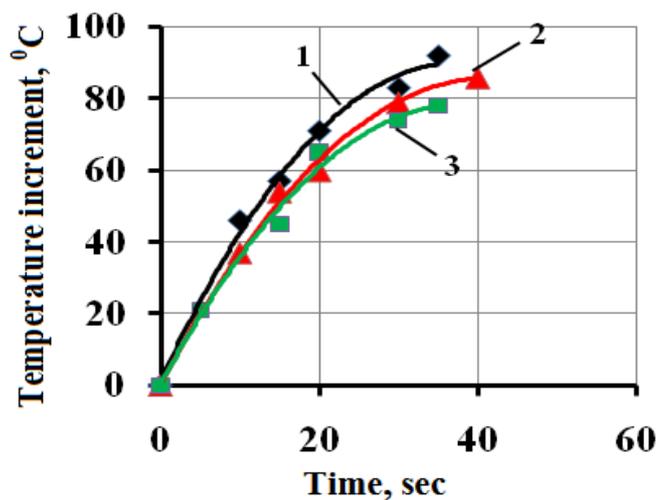**Figure 6** The relationship between a temperature increment of a RUNO-type spelt cereal and a heat time (the irradiance – 23 kW.m^{-2}, ambient temperature – 303 ºC) at moisture content, %: 1 – 12; 2 – 16; 3 – 22.

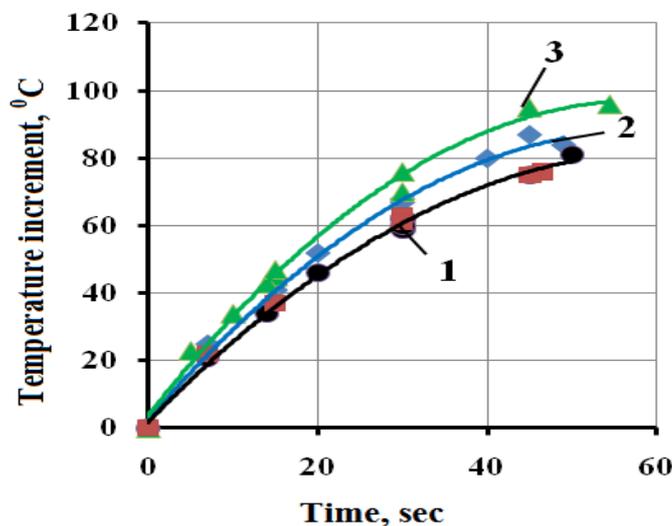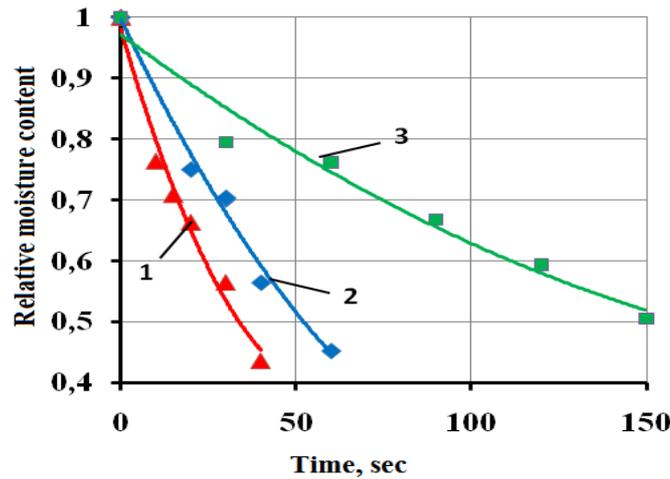**Figure 7** The relationship between a temperature increment of triticale grain and a heat time (the irradiance – 16 kW.m^{-2}, ambient temperature – 300 ºC) at moisture content, %: 1 – 18; 2 – 13; 3 – 10.
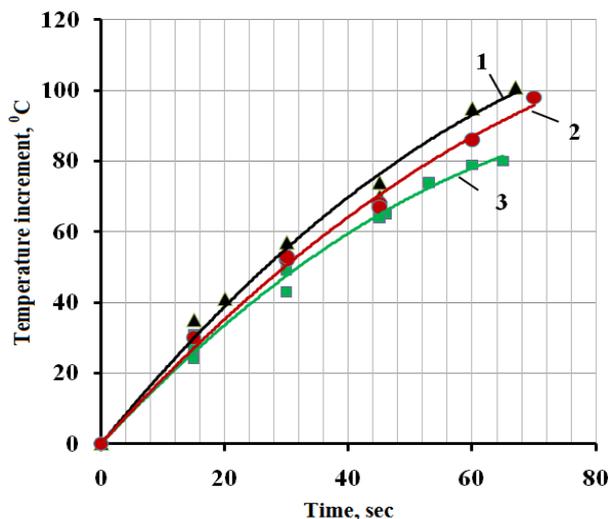
Figure 8 The relationship between a temperature increment of white lupine and a heat time (the irradiance – 15 kW.m^{-2}, ambient temperature – 263 ºC) at moisture content, %: 1– 7; 2 – 12; 3 – 17.

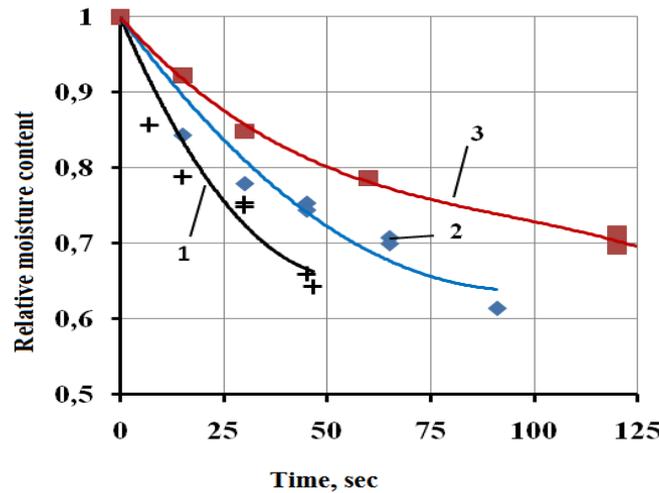100 °C, and the rate of moisture loss increases sharply.

Figure 9 The relationship between a relative moisture content of a RUNO-type spelt cereal with initial moisture content of 18%, and a heat time at the different irradiance E and ambient temperature T_c: 1 – E = 23 kW.m^{-2}, T_c = 303 ºC; 2 – E = 11 kW.m^{-2}, T_c = 270 ºC; 3 – E = 0 kW.m^{-2}, T_c = 212 ºC.

Figure 10 The relationship between a relative moisture content of triticale with initial moisture content of 18%, and a heat time at the different irradiance E and ambient temperature T_c: 1 – E = 16 кВт/м^2, T_c = 271 ºC; 2 – E = 10 кВт/м^2, T_c = 204 ºC; 3 –E = 0 кВт/м^2, T_c = 148 ºC.

A model of the convective-radiation heating

Taking advantage of using the first two terms of the series (1), and setting the coefficients to be constant, for the initial conditions $\Delta T(0) = 0$, a model of heating can be represented in the form

$$\Delta T(t) = K_0[1 - \exp(-K_t t)]. \qquad (2)$$

where $\Delta T = (T - T_0)$,

K_0, K_t – empirical coefficients.

The coefficients are assumed to be constant in time, but dependent on the heating conditions (initial humidity, irradiance and ambient temperature in the treatment zone). It is obvious that the condition of constancy (slight change) in the coefficients is not satisfied in the entire temperature range. It is known from the experiments that the intensive dehydration begins near the temperature of product at

Therefore, the proposed dependence can be regarded as an initial, rather rude approximation.
Analysis of the coefficients, including on a number of other grain crops as well, has revealed a correlation of K_0 with the initial moisture content, and of K_t with treatment modes.

As a rule, in industrial installations, the irradiance and temperature in the treatment zone are constant, i.e. K_t = const. From the batch to the batch of grain, its moisture content may change, which primarily affects the coefficient K_0.

Correlation between the model coefficients and moisture content and heat treatment modes

Based on the results of multi-factorial experiment, the parameters K_0 and K_t of the temperature dependence (4) for white lupine grain, triticale, and spelt cereal were identified, and their dependence on moisture content and treatment modes was evaluated. The results are shown in Figure 15 and Figure 16.

The effect of moisture content was evaluated at fixed heat treatment modes. From the graphs in Fig. 15, the correlation of the coefficient K_0 with moisture content is clearly visible, while for K_t such a correlation is not observed (Figure 16).

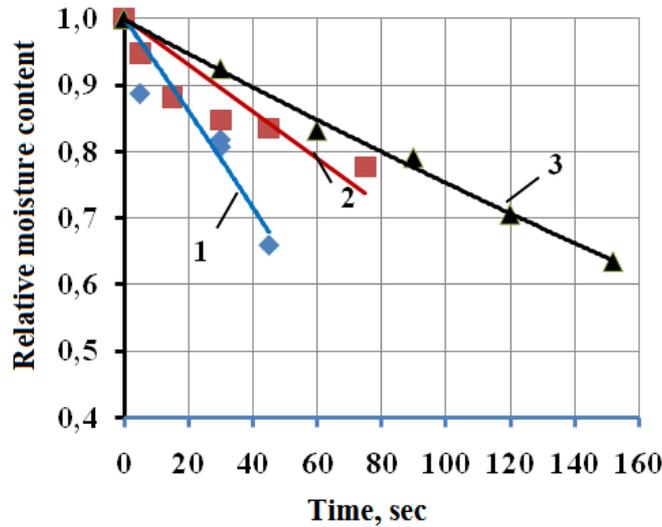It is a little more difficult to evaluate the effect of heating

Figure 11 The relationship between a relative moisture content of a DEGA-type white lupine with initial moisture content of 15%, and a heat time at the different irradiance E and ambient temperature T_c: 1 – E=22 кВт/м², T_c=301 ºC; 2 – E=13 кВт/м², T_c=223 ºC; 3 – E=0 кВт/м², T_c=177 ºC.
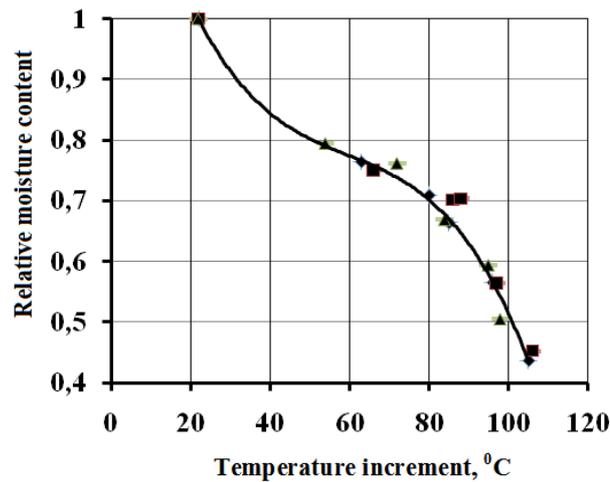

Figure 12 The relationship between a relative moisture content of a RUNO-type spelt cereal with initial moisture content of 18%, and a temperature at the different irradiance E = 0-23 kW/m² and ambient temperature T_c = 212-303 ºC.
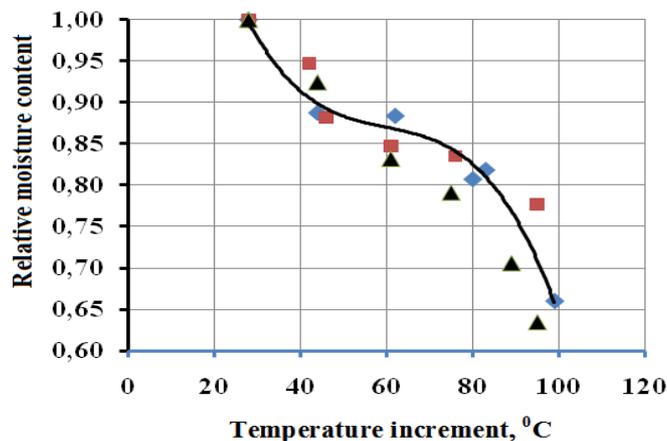

Figure 13 The relationship between a relative moisture content of triticale with initial moisture content of 18%, and a temperature at the different irradiance E = 0-16 kW.m⁻² and ambient temperature T_c = 148-271 ºC.
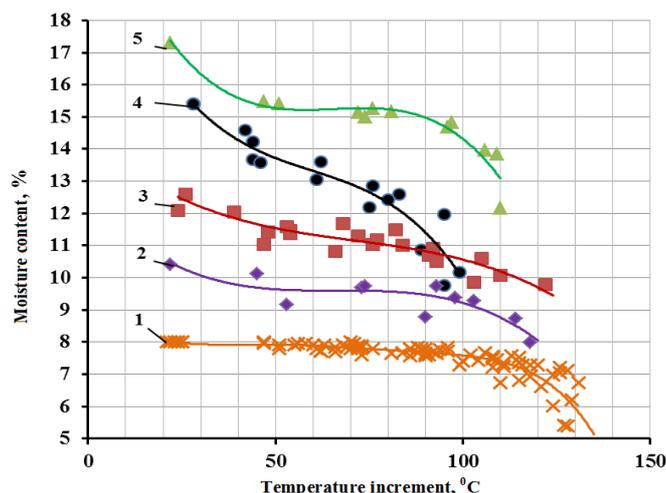
Figure 14 The empirical relationships between the change of moisture content of white lupine grain and a temperature at the different initial moisture contents and heat: 1 – initial moisture content – 8%, irradiance – 0 – 17 kW.m^{-2}, ambient temperature 157-308 ºC; 2 – initial moisture content – 10%, irradiance – 14 kW.m^{-2}, ambient temperature – 263 ºC; 3 – initial moisture content – 12%, irradiance – 0 – 22 kW.m^{-2}, ambient temperature – 183 – 301 ºC; 4 – initial moisture content – 15%, irradiance – 0 – 22 кВт/м^{2}, ambient temperature – 177 – 301 ºC; 5 – initial moisture content – 17%, irradiance – 14 кВт/м^{2}, ambient temperature – 263ºC.
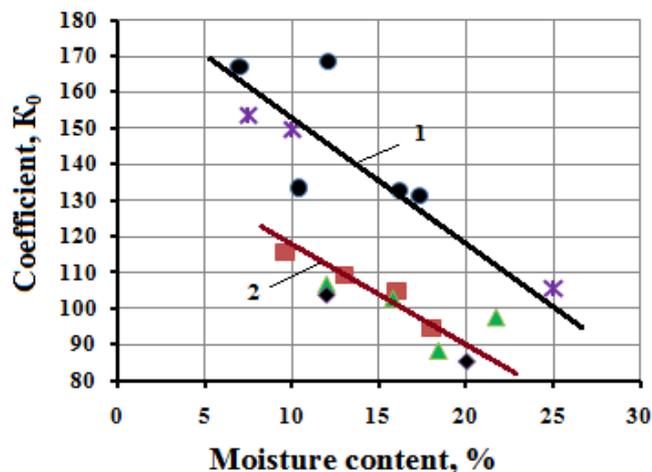

Figure 15 The dependence of coefficient K_0 on moisture content: 1 – lupine, the sunflower seed; 2 –triticale, spelt cereal and pearl barley.

modes, since a change in the irradiance leads to a change in the ambient temperature, and the evaluation of energy activity of the medium causes some difficulties.

A generalized model

Proceeding from the results of the analysis of the dependences of the model coefficients (2) on the initial moisture content of cereal and the ambient temperature in the treatment zone, a generalized model is proposed in the following form

$$\Delta T(t) = K0 \,(1- KwW \,)\{ \, 1 – \exp[–Kt(E + KT \, \Delta Tc) \, t]\}. \quad (3)$$

Based on the results of a complete set of initial experimental data, the model parameters were identified taking into account the effect not only of moisture content,

but also of heat treatment modes. The results of identification of model parameters (3) are given in Table 1.

A model of dehydration

We shall use the relationship (1). We shall confine ourselves to the first approximation, which, after substituting the model for the heating time (2) and the transformations, leads to a model for the relative current moisture content, as a function of a temperature increment

$$U/U_0 = (1 – \Delta T/ k_0)^{C}, \quad (4)$$

where ΔT – temperature increment, k_0 and C – empirical coefficients.

The value of the parameter k_0 can be taken from the results of the identification of the heating model
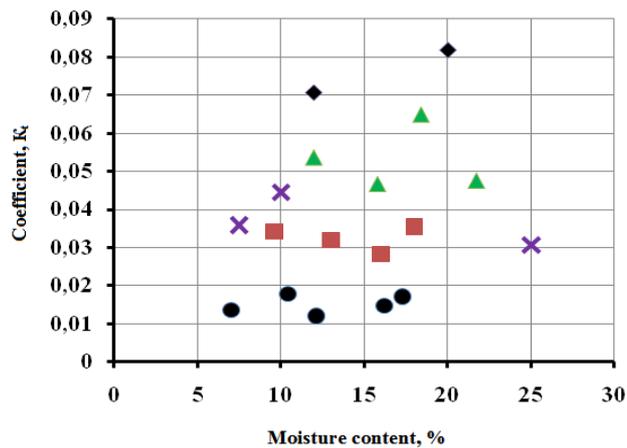
Figure 16 The dependence of coefficient K_t on moisture content: 1 – lupine, the sunflower seed; 2 –triticale, spelt cereal and pearl barley: ▲ – spelt; ■ – triticale; ● – lupine; ♦ – pearl barley; × – the sunflower seed.
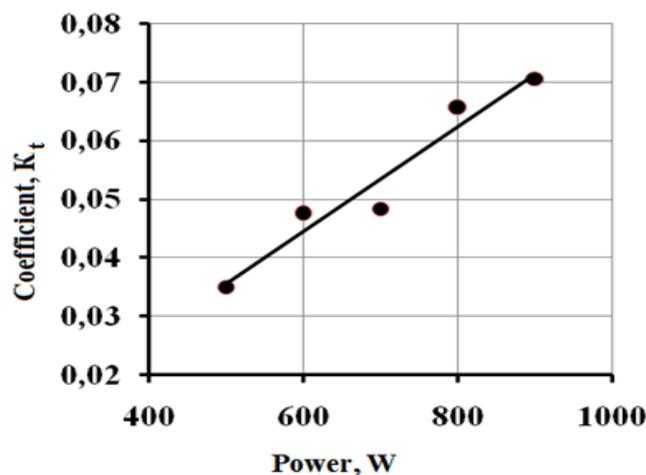

Figure 17 The dependence of coefficient K_t on the grossed installed capacity in the treatment zone of infrared emitters for pearl barley.
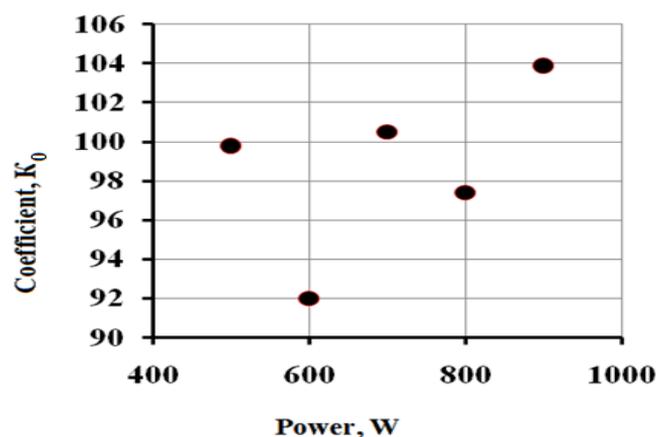

Figure 18 The dependence of coefficient K_0 on the grossed installed capacity in the treatment zone of infrared emitters

parameters or, just as the parameters B and C, may be identified by the results of dehydration experiments.

Identification of the parameter B and C by the results of the experiments with a wide variation in the initial moisture content, irradiance and temperature in the treatment zone, has shown a dependence on the initial moisture content and the absence of correlation with heating modes. As a result, a model is proposed

$$U/U_0 = (1 - \Delta T\, U_0/\, K_0)^C, \qquad (5)$$
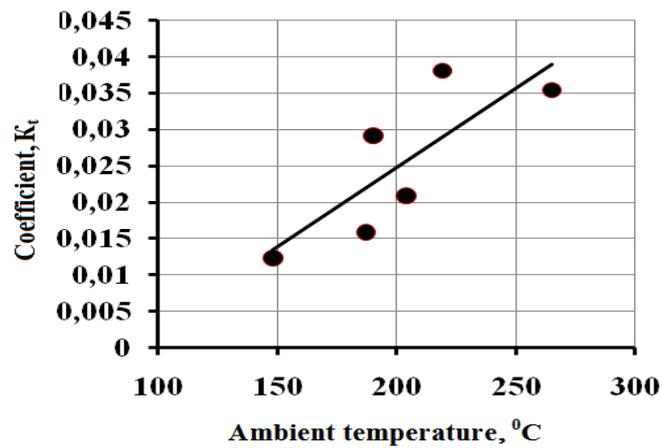
where U_0 – initial moisture content.

Figure 19 The dependence of coefficient K_t on the ambient temperature in the treatment zone for triticale grain.
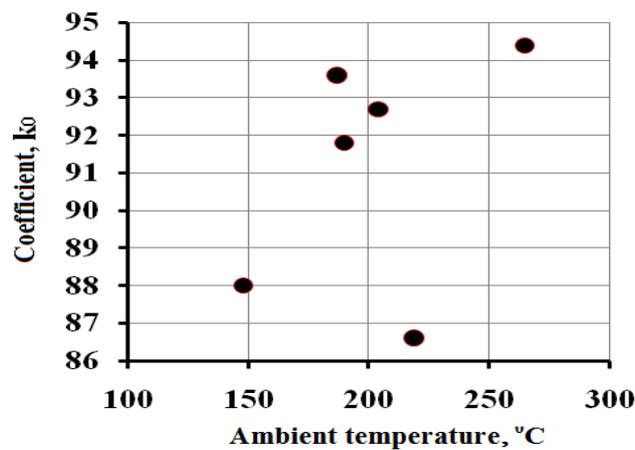

Figure 20 The dependence of coefficient K_0 on the ambient temperature in the treatment zone for triticale grain.

Table 1 Model parameters (3).

Type of product	K_0	K_T	K_t	K_w	Squared multiple correlation, R^2
Triticale grain	113.0	0.0714	0.00129	0.0125	0.993
Spelt cereal ("Runo")	121.1	0.0444	0.00149	0.0134	0.995
White lupine ("Dega")	128.3	0.2144	0.000298	0.00567	0.990

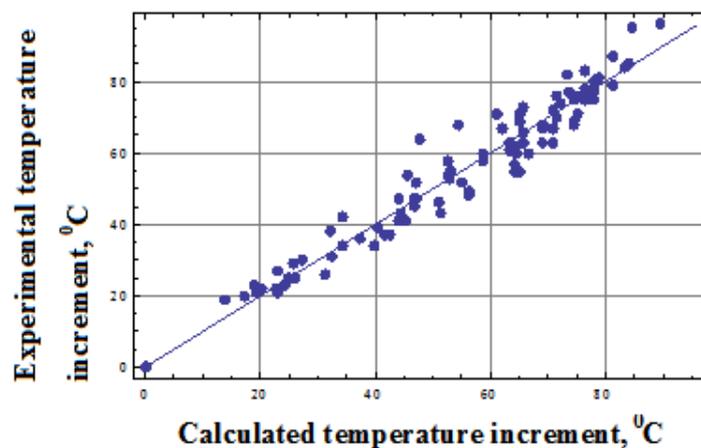Calculated by a model (3) and experimental values of grain temperature are shown in Figures 21 – 23.

Figure 21 Experimental and calculated values of a temperature increment of triticale grain when varying by the irradiance of 0 – 22 kW.m^{-2}, ambient temperature 148 – 347 ºC and initial moisture content W= 10…21%.
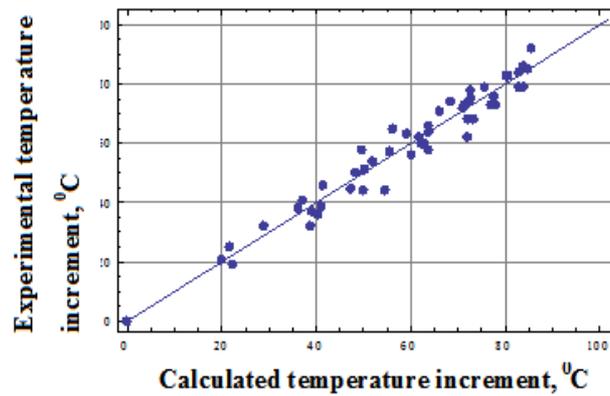
Figure 22 Experimental and calculated values of a temperature increment of spelt cereal when varying by the irradiance of 0 – 22 kW.m^{-2}, ambient temperature 132 – 313 ºC and initial moisture content W= 12…22%.
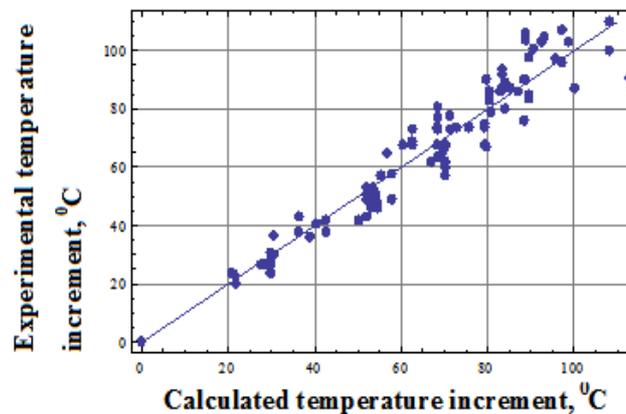

Figure 23 Experimental and calculated values of a temperature increment of white lupine when varying by the irradiance of 0 – 17 kW.m^{-2}, ambient temperature 142 – 275 ºC and initial moisture content W = 7…17%.

Table 2 Model parameters (4).

Type of product	K_0,	C	Squared multiple correlation, R^2
Triticale grain	27.3	0.44	
Spelt cereal ("Runo")	48.3	1.26	0.99
White lupine ("Dega")	30.4	0.32	

Calculated by a model (3) and experimental values of relative moisture content for triticale grain are shown in Figure 24.
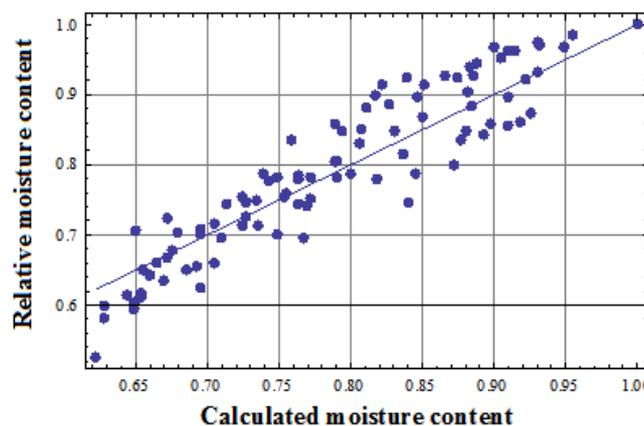

Figure 24 Calculated (K_0 = 27.3, C = 0.446, squared pair correlation R^2 = 0.998) and experimental values (initial moisture content U_0 = 0.11-0.27, irradiance E = 0-27 kW.m^{-2}, temperature in the treatment zone T_c=340 – 150 ºC) of relative moisture content for triticale grain.

However, it should be borne in mind that this model describes adequately the process of dehydration to an extent limited by the upper temperature value of grain not much more than 100 ºC.

However, it should be borne in mind that this model describes adequately the process of dehydration to an extent limited by the upper temperature value of grain not much more than 100 ºC. From the presented graphs (Figures 1.24 – 1.26) and earlier obtained results for barley and millet, it can be assumed that the model describes adequately experimental data on the small-sized (3 – 5 mm) objects.

CONCLUSION

Despite the assumptions made, the considered models describe adequately the grain temperature rise during infrared heating in the range of 10 – 100 °C and moisture content up to 15%. High correlation coefficients and a significant difference between the residual variance and the variance of the mean allow us to speak about the adequacy of models. We have to explain the physical reality of invariance of the dependence of moisture content on the temperature of infrared radiation.

Simplicity of models allows even in production conditions, having determined the coefficients of the model, to correct processing modes. At higher temperatures and initial humidity, more complex distributed models are needed.

An increase in the share of radiation heat supply, due to an increase in the absorption coefficient K_E, and due to the irradiance E, for example, as a result of more efficient design of the treatment zone, leads to a reduction in the heat time until a given temperature. In this case, we note that the nature of the change in the moisture content of the product does not change due to its invariance to the heating regimes.Ideally, all power of the emitter should be "pumped" into the product by the mechanism of radiation heating. This is understandable, because any excess temperature in the treatment zone above the ambient temperature leads to heat loss. Design activities should be aimed at minimizing heat losses, increasing the radiant efficiency of the emitter and the reflecting power of the screen system. However, the reduction of heat loss (due to the thermal insulation of the treatment zone) without increasing the reflecting power of screens leads to an increase in the ambient temperature to the value of infrared emitters or elements of design, which are unacceptable by the operating conditions.

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