ANALYSIS OF SOYBEAN DRYING DYNAMICS IN THIN LAYER

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Abstract. *To design dryers and develop efficient grain drying process the mathematical modeling and computer simulation are widely used. The approach of a thin-layer drying models can be used and the goodness of this models essentially defines the simulation results for bulk drying. The principal objectives of the present work are: to obtain an experimental data on soybean drying dynamics at different temperatures, airflow velocities and air relative humidity for varies initial moisture contents of seed; to adapt/create a mathematical thin-layer drying model for soybean; to validate the model with experimental data adjusting the heat and mass transfer coefficients and the moisture diffusivity. Experimental equipment was developed and used to obtain the thin-layer drying data. Thin-layer drying dynamics tests were conducted for soybean in the temperature range 45-110ºC, velocity range 0-3 m/s, air relative humidity range 10-50% and variation of grain moisture content 13-32%. To generate air of required humidity the water vapor was injected after the air heater. Rate of influence of these parameters on drying ratio is varied during drying process. The dominant factor in initial time is mass transfer on the contact surface between soybean seed and air. In posterior time a diffusion process inside soybean seed begins to limit a mass flux rate, turning in a dominant factor. With increase of initial grain moisture content at the same temperature the drying rate in an initial stage increases. With time this rate decreases and ceases to depend on initial grain moisture content. With augmentation of temperature the drying rate increases at all values of initial grain moisture content. The increase of air velocity in the investigated interval leads initially to acceleration of drying process for all moisture contents and temperatures, specifying an essential role of mass transfer on grain periphery. This increase is more essential for drying at higher temperatures. With reduction of moisture content during drying the role of mass diffusion inside grain increases and velocity influence reduces. At absence of airflow (V=0) the drying ratio practically does not depend on moisture content for initial moisture contents, greater than of 19 %. At small moisture contents (13 %) the drying process is essentially slowed down. To use the obtained results in models of deep beds it was proposed to consider the soybean seed composed by two compartment with different transfer coefficients, considering the effects of diffusion coeficient in 1-st and 2-st compartment and convective transfer on a surface of grain. The mathematical model is presented by system of two ordinary differential equations.*

Keywords*: soybean drying, thin-layer drying, mathematical modeling, heat and mass transfer coefficients*

1. INTRODUCTION

Due to a humid climate during harvesting of soybean the moisture content of seed is very high, up to 24-28 % dry basis, (d.b.). Therefore practically all soybean crop before the beginning of storage is exposed to process of drying. Considering immense volumes of a crop, even minor improvement and acceleration of drying process gives significant economic benefit.

So the drying process in dryers presents some requirements: should be quick, because the flow of grain supply in the storage units can not be stopped at harvest time; must be efficient, where a prescribed amount of water needs to be removed so that the grain reach the moisture content appropriate for the storage; should be safe because the grain can not suffer damage that affect their future purpose; and should be economical, being carried out with minimal operating cost. To meet these requirements is necessary to know and monitor the physical phenomena present in the drying process of industrial dryers and in this sense, the mathematical modeling and the numerical simulation combined with experimental results in an efficient alternative and the low cost.

To design dryers and develop efficient grain drying process the mathematical modeling and computer simulation are widely used (Courtois *et.al.*, 1991). There are various mathematical models to describe the drying process. These models consider the heat and mass transfer between grain and air, the heat and moisture transfer inside of grain, a deviation from equilibrium state between grain and drying air, variation of physical properties of air, vapor and grains with temperature and humidity variation (Parry, 1985, Khatchatourian *et.al*., 2003).

Generally these models represent a system of the energy and moisture transfer differential equations for an individual grain located in a layer, the heat and mass transfer differential equations for a surface of a grain, where there is a contact of air and grain, and the energy and mass conservation equations of the humid air (Brooker *et. al*., 1982, Khatchatourian and Oliveira, 2006).

Nonlinearity of these equations does not allow to receive analytical solution for interesting applied cases. Used numerical methods (finite difference method, finite element method, etc.) represent integration domain (drying camera) as the subdomains set in which for a finding of any parameter during each moment of time is selected a simplified interpolation equation (usually linear or square-law). Because of subdomain sizes smallness the parameters change inside subdomain is insignificant; therefore for calculation of the local mass flow and heat flow densities the approach of a thin-layer drying model can be used. Thus, the goodness of thin-layer drying models essentially defines the simulation results for bulk drying.

There are some thin-layer drying equations for soybean in the literature (Soares, 1986; White *et. al*., 1981, Osborn *et.al*., 1992, Hutchinson and Otten, 1983, ASAE, 1998). At the same time the variation interval of experimental data to obtain these equations not always was sufficient. Besides practically there are no reliable data on influence of air velocity and initial air humidity on dynamics of drying in a thin-layer. Considering the tendency to an intensification of drying process, complication of dryers layout and use of wider interval of change of initial parameters variation (temperature, drying air velocity, and air humidity variation inside drying camera) there is a necessity for additional researches of thin-layer model for soybean.

The principal objectives of the present work are:

a) to obtain an experimental data on soybean drying dynamics at different airflow velocities and temperatures for varies initial moisture contents of seed;
b) to adapt/create a mathematical thin-layer drying model for soybean;
c) to validate the model with experimental data adjusting the heat and mass transfer coefficients and the moisture diffusivity.

2. MATHEMATICAL MODEL

2.1. Concept of thin-layer

Despite of wide use, the concept of thin layer requires some specification. For example, Jayas *et. al*. (1991) defined a thin layer as "a thickness meeting the requirement that the temperature and relative humidity of the drying air does not change when passing through the grain layer in the drying process". But actually, local values of these parameters vary as a result of the heat and mass transfer between grain and air. Therefore it is pertinently to specify a difference between the thin layer concepts, used in mathematical models and in experimental researches. The models based on the thin layer concept use continuous functions of distribution of grain and air parameters in a layer, considering the heat and mass transfer between grain and air in source terms of the corresponding equations. For 2D (crossflow grain dryers) and 3D models the thin layer concept loses sense as there are no layers with identical characteristics. Therefore the thin layer equations used in these models play a role of local (point or linear) source power (mass or heat). To receive the empirical thin layer equations in experimental researches, it is necessary to satisfy next conditions: 1) the change of average relative humidity and air temperature at passage through a layer of grain should be infinitesimal; 2) the change of moisture content and grain temperature on depth of a layer should be infinitesimal (in comparison with time variation).

2.2. Two compartment model for thin-layer drying of soybean

In this work the two-layer grain model has been chosen, considering non uniform distribution of moisture inside the grain. The mathematical model is presented by system of two ordinary differential equations.

The modeling considers the gradient of moisture content within the grain through a representation of the grain in two concentric compartments.

The mass of water in grain (m_{wg}) is represented by:

$$m_{wg} = m_g \, M = \rho_g \, V_g \, M \tag{1}$$

where: m_g is the mass of dry grain (kg); M is the average moisture content of grain (decimal); ρ_g is density of grain (kg/m^3); V_g is the volume of grain (m^3).

Defining τ_i as the volume ratio (volume of compartment divided by total volume of the grain) in compartment i (i=1,2), the mass of water in the grain in the compartments is:

$$m_{wgi} = \rho_g \, V_g \, \tau_i \, M_i \tag{2}$$

The average moisture content of grain is:

$$M = M_1 \tau_1 + M_2 \tau_2 \tag{3}$$

where: τ_1 and τ_2 are the ratio of volume in the compartments 1 and 2, respectively (dimensionless); M_1 and M_2 are the average moisture content in the compartments 1 and 2, respectively (decimal).

For the first compartment the flow rate of moisture diffusion between compartments 1 and 2 can be written as:

$$\frac{\partial(m_{wg1})}{\partial t} = -D_{12} = \frac{\partial}{\partial t}(\rho_g V_g \tau_1 M_1) = \rho_g V_g \tau_1 \frac{\partial M_1}{\partial t} \tag{4}$$

where: t is the time (s); D_{12} is the rate of water flow between compartments 1 and 2 (kg/s).

The rate of mass transfer inside the grain is determined by:

$$\frac{\partial(m_{wg1})}{\partial t} = -D_{12} = -k_{12}(M_1 - M_2) = -B_1 V_g (M_1 - M_2) \tag{5}$$

where B1 is the coefficient of mass transfer between compartments (kg/s.m^3).

From the equations (4) and (5) arrives at:

$$\frac{\partial M_1}{\partial t} = -k_1(M_1 - M2) \tag{6}$$

k_1 is the drying constant or coefficient of proportionality (s^{-1}).

For the second compartment should take into account the effect of diffusion within the grain and also the mass transfer by convection at the surface of the grain. The representation of this compartment is suggested as:

$$\frac{\partial M_2}{\partial t} = -k_1(M_2 - M_1) - qk_2(M_2 - M_e)^n \tag{7}$$

where: k_2 is the drying constant (s^{-1}); q is a factor that considers the influence of air velocity on drying (dimensionless); M_e is the equilibrium moisture content (decimal); n is a constant (dimensionless).

The two-compartment mathematical model for drying thin layer is presented by a system of two ordinary differential equations:

$$\begin{cases} \dfrac{\partial M_1}{\partial t} = -k_1\left(M_1 - M_2\right); \\ \dfrac{\partial M_2}{\partial t} = -k_1\left(M_2 - M_1\right) - q \cdot k_2\left(M_2 - M_e\right)^n \end{cases} \tag{8}$$

Obviously, k_1 is related with a diffusion coefficient in 1-st compartment and k_2 unites the effects of diffusion in 2-st compartment and convective transfer on a surface of grain.

Applying the moisture ratio average of the grain, the systems can be presented in form:

$$\begin{cases} \dfrac{\partial MR_1}{\partial t} = -k_1\left(MR_1 - MR_2\right); \\ \dfrac{\partial MR_2}{\partial t} = -k_1\left(MR_2 - MR_1\right) - q \cdot k_2\left(M_0 - M_e\right)^{n-1} MR_2^n \end{cases} \tag{9}$$

The moisture ratio average (MR) of the grain is defined by:

$$MR = \frac{M - M_e}{M_0 - M_e} \tag{10}$$

M_0 is the initial moisture content of grain (decimal).

Second equation in system (9) presents the influence of drying rate from: a) initial moisture content M_0 and, b) air humidity through equilibrium moisture content M_e. As experimental data show the coefficients k_1 and k_2 depend on temperature. The influence of initial moisture content on k_1 and k_2 can be neglected. To consider the velocity influence on drying, the coefficient k_2 was multiplied by factor:

$$q = \frac{2.3306}{1+e^{-2v}} - 1 \tag{11}$$

that is equal to 1 when V=0.9 m/s (basic velocity).

Using the method of inverse problem the coefficients k_1 e k_2 were obtained for different moisture contents initials and temperatures, for the same initial velocity v=0.9 m/s. The problem is solved by minimizing an objective function through the method of least squares. The function is defined as:

$$S = \min_{k_1,k_2} \sum_{i=1}^{N} \left[M_{\text{measured values}} - M_{\text{calculated values}}\right]^2 \tag{12}$$

where N is the total number of measurements of the moisture M taken during the experiment.

3. EXPERIMENTAL STUDY

Figure 1 shows the experimental equipment used to obtain the thin-layer drying data. The equipment consists of ventilating fan, orifice plate, heat booster, systems of steam generation and injection, system of data acquisition and thin-layer drying box.

The thin-layer drying box consists of a cylindrical metal tube of small height with an internal screen, in which is placed a grain mass of approximately 200 grams. The mass of grain in the thin-layer drying box is determined on an analytical balance at regular interval of time. In the entrance region of thin-layer is measured the temperature and the humidity of the drying air. This procedure allows to obtain the soybean drying dynamics.

Thin-layer drying tests were conducted for soybean in the temperature range 45-110^{o}C, velocity range 0.05-3 m/s, grain moisture content 13-32% with variation of air relative humidity (10-50%). To generate air of required humidity the water vapor was injected after the air heater. All of experiments were realized with replication to guarantee the data reliability.

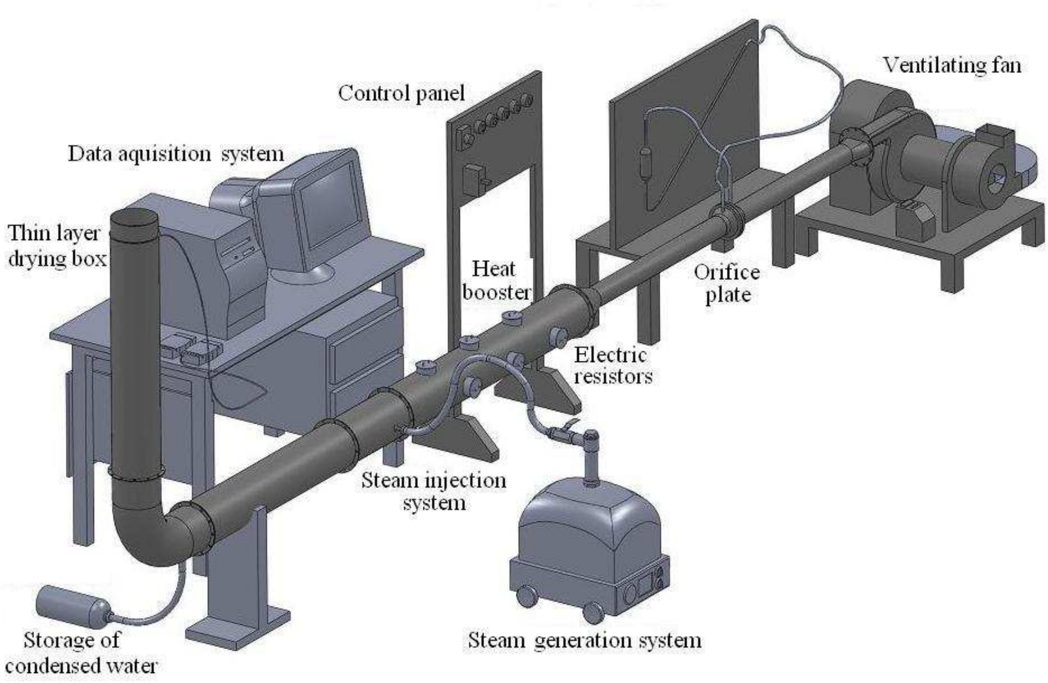

Figure 1. Experimental equipment developed for tests.

4. RESULTS AND SIMULATION

In Figs. 2-7 some of the received experimental data on drying soybean dynamics are presented. Satisfactory concordance between these data and Soares (1986) data, presented in Figs. 2 and 3, confirms reliability of the chosen measurement technique. As these Figs. show, with increase of initial grain moisture content at the same temperature the drying rate in an initial stage increases.

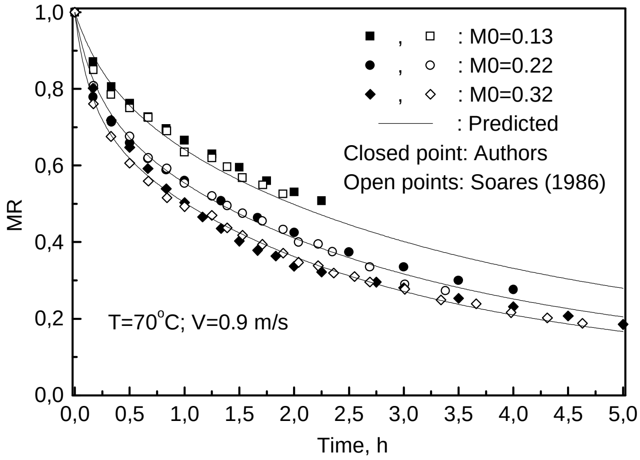

Figure 2. Soybean drying dynamics in a thin-layer at different initial grain moisture contents: T=70ºC

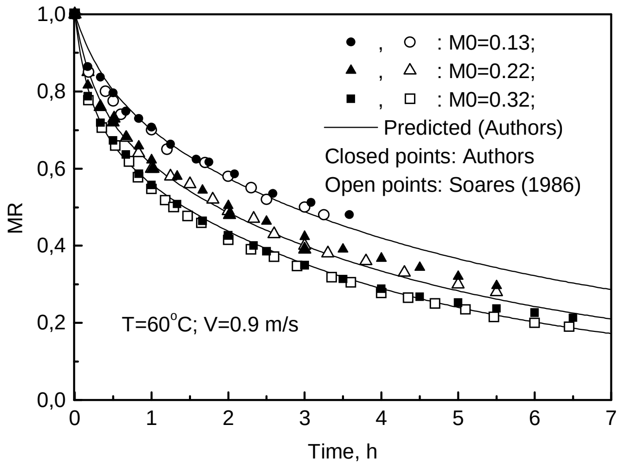

Figure 3. Soybean drying dynamics in a thin-layer at different initial grain moisture contents: T=60ºC.

With time this rate decreases and ceases to depend on initial grain moisture content (Fig. 4). With augmentation of temperature (Fig. 5) the drying rate increases at all values of initial grain moisture content.

The augmentation of air velocity initially (from 0 m/s up to 0.9-1 m/s) leads to acceleration of drying process (Fig. 6). This shows an essential role of mass transfer on periphery of grain for small air velocities for initial drying period. Posterior augmentation of air velocity quasi does not intensify drying process. With decrease of grain moisture content as a result of drying the role of moisture diffusion inside grain increases and the influence of air velocity on drying process is decreasing.

In the absence of air stream (V=0) the rate of reduction of grain moisture content practically does not depend on initial grain moisture content (for initial concentration greater than 0.19). At small moisture content (<0.13) the drying rate is essentially slowed down.

Figure 7 presents the curves of soybean drying dynamics in thin- layer for two same initial moisture contents (0.13 b.s. and 0.19 b.s.). Curves with closed points correspond to the case of natural "initial" distribution (or "uniform") of moisture inside of grain, when the grains were submitted during a long period to equalizing of moisture before drying process (uniform "humidity" case).

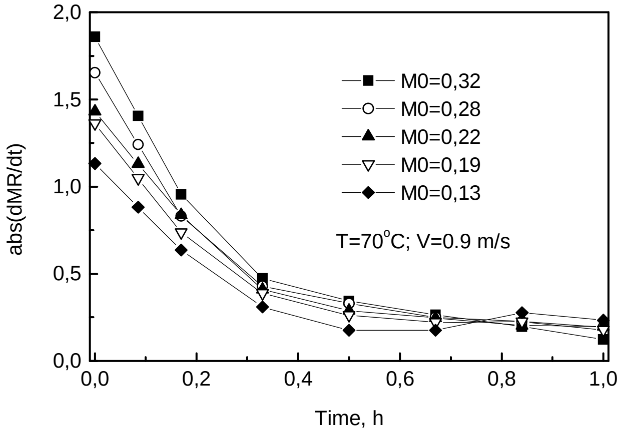

Figure 4. Dynamics of absolute drying rate variation in a thin layer at different initial grain moisture contents

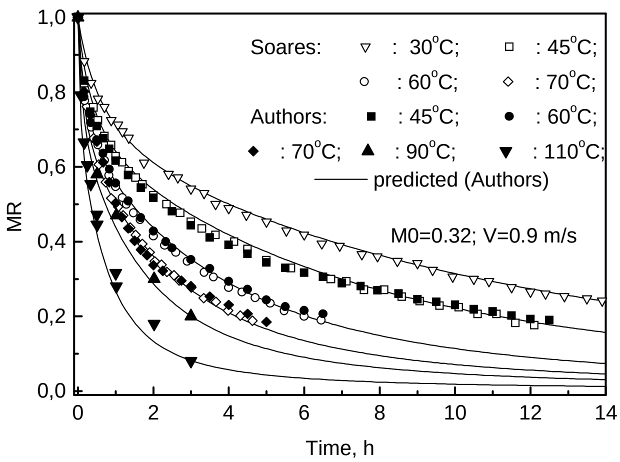

Figure 5. Temperature influence on soybean drying dynamics.

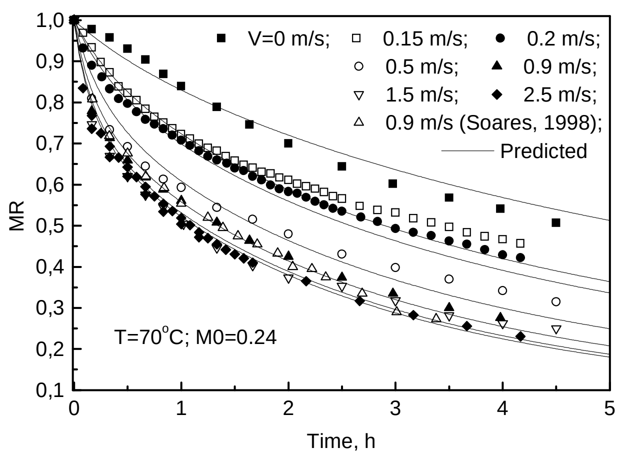

Figure 6. Velocity influence on soybean drying dynamics.

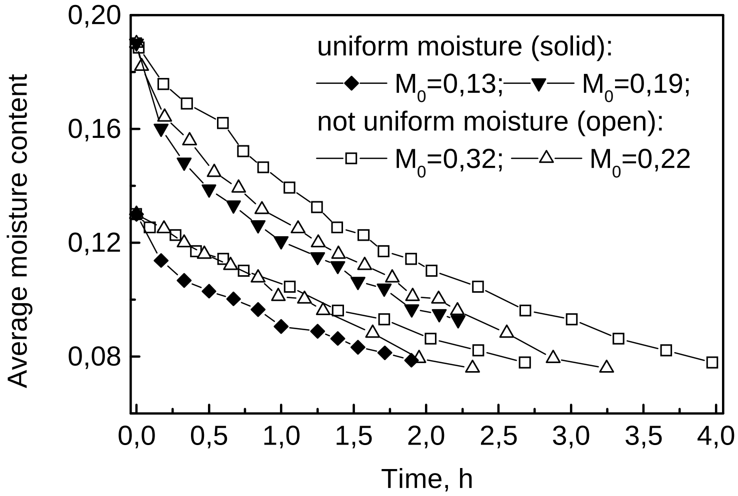

Figure 7. Soybean drying dynamics in thin- layer with "uniform" and "non uniform" initial distribution of moisture inside of grain.

Curves with open points present an immediate continuation of drying of the grains with initial moisture content of 0.32 or 0.22 just after reaching the medium value of moisture content the same to 0.19 and later 0.13 ("non uniform" case). It can admit that significant fall of drying rate in the "non uniform" case is conditioned by the concentration reduction in the peripheral layers of the grain during of drying. This indicates that during of the drying process the rate of mass transfer between air and grain surface (mass flux) in the initial moments, when the moisture concentration in the peripheral layers of the grain is relatively high, is determined by the process of mass transfer on the contact surface between the grain and the air. In posterior moments the diffusion begins to limit the passage of water inside of the grain and the concentration in the periphery of the grain is diminishing, reducing the intensity of mass flow.

Thus, moisture distribution in grain essentially influences rate of drying. At identical average concentration of grain moisture, rate of drying is not constant and depends of moisture distribution uniformity. Than more water quantity the grain lost up to current moment, the rate of drying is less. The moisture leaves a grain from a surface, thus it is logical to assume, that there is more non-uniform distribution of moisture on radius for grain with greater initial concentration in comparison with other grains. Thus the more wet part is concentrated in the central part of grain and more dry in the periphery. At a constant diffusion coefficient the transfer of moisture to periphery in these conditions should grow because of a greater gradient of concentration, i.e. have the opposite effect than observed. Considering, that the increase of drying rate is limited with the air velocity increase (Fig. 8), i.e. convective mass transfer is limited, it is possible to assume, that the diffusion coefficient has variable value in a radial direction. These reasonings allow to present conditionally each grain consisting of the several parts, differing by value of a diffusion coefficient.

So, the drying model should consider as water diffusion process and non-uniform distribution of moisture on radius inside of grain, and mass transfer on contact surface between grain and air.

As experimental data show (Figs. 8 and 9) the coefficients k_1 and k_2 depend on temperature.

The continue curves in Figs. 2, 3, 5 and 6 present simulation by proposed model. Compartment volumes were assumed equals and n=2.

Figure 10 presents the influence of air relative humidity on thin-layer drying. The value RH=5% at T=70 ºC corresponds to natural air humidity 66% at T= 20°C, reduced by air heating from 20°C up to 70ºC. The values of RH 20% and 30% are obtained by vapor injection in heat booster.

Initially, the increase of air humidity does not alter significantly drying process. When the value of RH runs up to 30%, the decrease of drying process becomes substantial.

In model the influence of air relative humidity on drying dynamics is implemented by the equilibrium moisture content M_e. In spite of correct qualitative direction of this influence, its quantitative estimation must be improved.

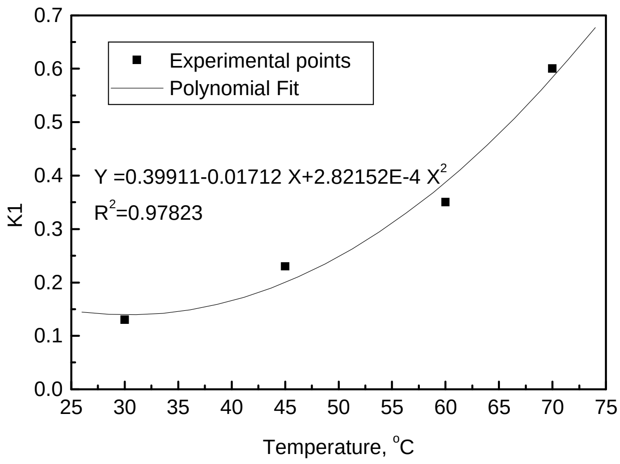

Figure 8. Dependence of coefficient k_1 from drying temperature.

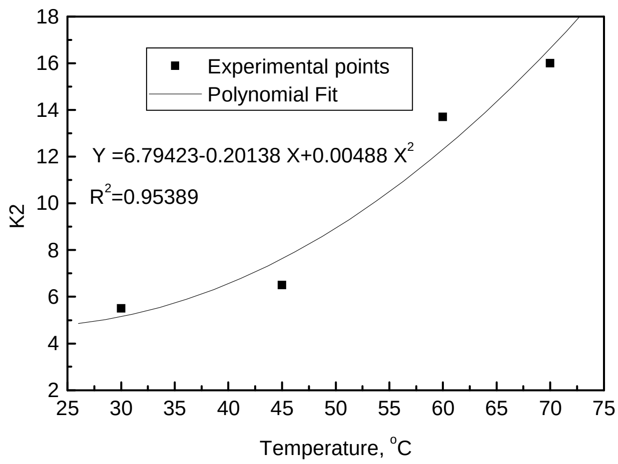

Figure 9. Dependence of coefficient k_2 from drying temperature.

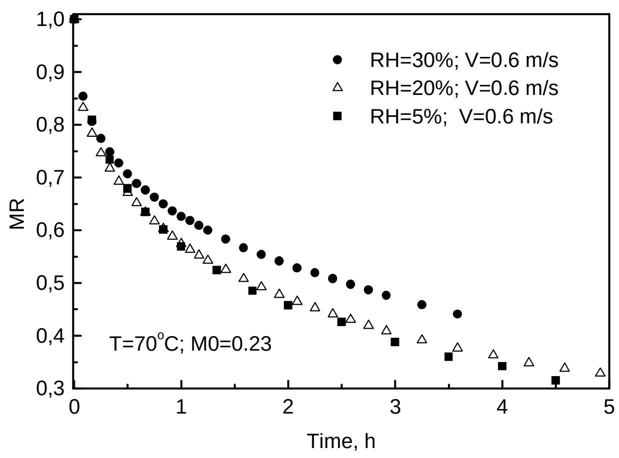

Figure 10. Influence of air relative humidity on thin-layer drying.

5. CONCLUSION

Experimental equipment was developed to study soybean thin-layer drying dynamics in the temperature range 45-110oC, velocity range 0-3 m/s, grain moisture content 13-32% with variation of air relative humidity (10-50%). It was showed that rate of influence of these parameters on drying ratio is varied during drying process. The dominant factor in initial time is mass transfer on the contact surface between soybean seed and air. In posterior time a diffusion process inside soybean seed begins to limit a mass flux rate, turning in a dominant factor. The increase of air velocity in the investigated interval leads initially to acceleration of drying process for all moisture contents and temperatures, specifying an essential role of mass transfer on grain periphery. With reduction of moisture content during drying the role of mass diffusion inside grain increases and velocity influence reduces. To similar soybean thin-layer drying dynamics the two-layer grain model has been chosen considering the soybean seed composed by two compartments with different transfer coefficients. The mathematical model is presented by system of two ordinary differential equations.

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