# SOYBEAN DRYING IN THIN-LAYER: EXPERIMENTAL AND THEORETICAL STUDY

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***Abstract.*** *Thin-layer drying tests were conducted for soybean in the temperature range 45-100$^o$C, velocity range 0.05-3 m/s, grain moisture content 13-30% with variation of air relative humidity (10-50%). To generate air of required humidity the water vapour 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. 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. It has been shown that the drying rate depends on non-uniformity of moisture content into a grain and mass diffusion coefficient is not constant inside of grain. In this work it was proposed to consider the soybean seed composed by two compartments with different mass diffusion coefficients. The mathematical model developed to describe the soybean drying in thin-layer is presented by system of two ordinary differential equations. The simulation and experimental data showed satisfactory concordance.*

***Keywords***: *grain 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.

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. Notion of thin-layer

Despite of wide use, 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. Distributed parameter model

According to Parti (1993), there are three main groups of thin-layer drying models: a) distributed parameter models; b) lumped parameter models; and c) thin-layer drying equations.

For the development, analysis, and optimization of new layouts of dryers, the distributed parameter models are more preferable, because allow to estimate influences of different parameters on processes of the heat and mass transfer. Besides, the validity of use of simple models usually is proved by comparison with fuller models demanding much more numerical and mathematical efforts and knowledge of greater number of parameters.

Damp soybean seed represents a system of a capillary-porous body and the connected substance in the form of a liquid, a vapor and air. The heat and mass transfer in this system occurs generally at presence of non-uniformity of temperature, concentration and pressure distributions, i.e. under action of three gradients: $\nabla T$, $\nabla\theta$ and $\nabla p$, where: $T$ is the local temperature inside the capillary porous body in $^{o}$C; $\theta$ is the mass transfer potential, dimensionless; $p$ is the local pressure inside the capillary porous body in Pa. If the vapor does not enter in a body from external sources, and vapor generation in a body occurs due to evaporation of the liquid inside of the body, the change of moisture content under all conditions can be calculated by the use of a liquid flux through a control surface, having taken for a basis the law of a liquid transfer (instead of vapor).

A mathematical model for a local domain of a capillary porous body has a form (Luikov and Mikhailov, 1963; Luikov, 1966):

$$\frac{\partial T}{\partial t} = a_q \nabla^2 T + \frac{f H_v c_m}{C_q}\frac{\partial \theta}{\partial t} \tag{1}$$

$$\frac{\partial \theta}{\partial t} = a_w \nabla^2 \theta + a_w \delta_\theta \nabla^2 T + a_w \frac{\lambda_p}{\lambda_w}\nabla^2 p \tag{2}$$

$$\frac{\partial p}{\partial t} = a_p \nabla^2 p - \frac{f c_m}{C_q}\frac{\partial \theta}{\partial t} \tag{3}$$

where: $t$ is the time in s; $T$ is the local temperature inside the capillary porous body in $^{o}$C; $a_q$ is the heat conductivity in m$^2$ s$^{-1}$; $f$ is the phase transformation coefficient, dimensionless; $H_v$ is the latent heat of water vaporization, J kg$^{-1}$; $a_w$ is the moisture diffusivity coefficient in m$^2$ s$^{-1}$; $c_m$ is the isothermal specific mass content, dimensionless; $\delta_\theta$ is the thermogradient coefficient in K$^{-1}$; $C_q$ is the specific heat of capillary porous body in J kg$^{-1}$ K$^{-1}$; $\theta$ is the mass transfer potential, dimensionless; $p$ is the local pressure inside the capillary porous body in Pa; $\lambda_p$ is the moisture permeability coefficient in s; $\lambda_w$ is the moisture conductivity in kg m$^{-1}$ s$^{-1}$; $\lambda_q$ is the thermal conductivity in W m$^{-1}$ K$^{-1}$.

The pressure gradient $\nabla p$ inside of a body arises at intensive heating of a damp body at T>100°C or due to pressure difference between mediums which are divided by a porous wall, for example, at a vacuum drying. If to exclude these drying cases, the equation (3) and the term, containing the pressure Laplacian, in the second equation disappear from the local equations system.

Heating/cooling process of a grain occurs much more intensively than moving of a moisture inside of grain (approximately in 10000 times, because Luikov number $Lu=a_q/a_w$ has order of magnitude $10^{-4}$). Therefore during heating/cooling the derivative $\partial\theta/\partial t$ is essentially less than $\partial T/\partial t$ and the last term in (1) can be neglected. Besides in experiment conditions of thin-layer drying the temperature field is equalized very quickly (in comparison with drying time), hence, the term with the temperature Laplacian in the equation (2) can be neglected (equilibrium temperature).

Considering a seed of soybean as a sphere and admitting that moisture content in each grain point for determined time $t$ is a function of radius-vector $r$ of this point, the thin layer drying problem for a seed can be presented by equation:

$$\frac{\partial U(r,t)}{\partial t}=\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 D\frac{\partial U(r,t)}{\partial r}\right) \tag{4}$$

Absorption of moisture from a surface of grain in bound condition is considered proportional to a difference between air humidity on this surface and in drying air:

$$D\frac{\partial U(r,t)}{\partial r}+H\cdot(Y_s-Y_a)=0, \tag{5}$$

or as it is accepted in the present work, proportional to a difference between local moisture content in seed surface and equilibrium moisture content:

$$D\frac{\partial U(r,t)}{\partial r}+H\cdot\left(U(R,t)-U_e\right)=0 \tag{6}$$

Initial condition:

$$U(r,0)=\Psi(r). \tag{7}$$

In these equations:

$U=U(r,\, t)$ is local grain moisture content; $Y$ is humidity ($kg_{water}/kg_{air}$); $U_e$ is equilibrium moisture content; $D$ is the diffusion coefficient, $H$ is the mass transfer coefficient; $R$ is sphere radius (grain), $\Psi(r)$ is a function that determines a initial distribution of water inside of sphere.

Denoting $M=\dfrac{U-U_e}{U_0-U_e}$ (relative grain humidity), $\varphi(r)=\dfrac{\Psi(r)-U_e}{U_0-U_e}$, and $h=H/D$ the problem can be presented by the equations:

$$\frac{\partial M}{\partial t}=\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 D\frac{\partial M}{\partial r}\right), \tag{8}$$

$$\frac{\partial M}{\partial r}+h\cdot M=0, \tag{9}$$

$$M(r,0)=\varphi(r). \tag{10}$$

Applying the Fourier and Biot criteria:

$$Fo_m=\frac{Dt}{R^2};\; Bi_m=\frac{HR}{D}=hR=p-1,$$

and assuming an uniform distribution of initial water concentration inside of seed $\varphi(r)=1$, solution can be presented in form:

$$M(r,t)=\frac{2}{r}\sum_{n=1}^{\infty}\frac{(Bi_m-1)^2+\mu_n^2}{(Bi_m-1)Bi_m+\mu_n^2}\cdot\frac{\sin\mu_n-\mu_n\cos\mu_n}{\mu_n^2}\cdot\sin\mu_n r\cdot e^{-\mu_n^2 Fo_m} \tag{11}$$

where $\mu_n$ is nth root of the equation:

$$\mu\cos\mu+(Bi_m+1)\sin\mu=0\,. \tag{12}$$

Figure 1 shows a contribution of various harmonic components which constitute the sum (11) for average value of moisture content of the grain $\overline{RU}(t)$ in the course of the drying:

$$\overline{M}(t)=\frac{3}{R^3}\int_0^R M(r,t)r^2dr \tag{13}$$

It can be seen that the first component $M_1$ (n=1) is more significant than the sum $M$ of all others. With time (Fourier number $Fo_m$ is a relative time) the influence of this harmonic component becomes predominant.

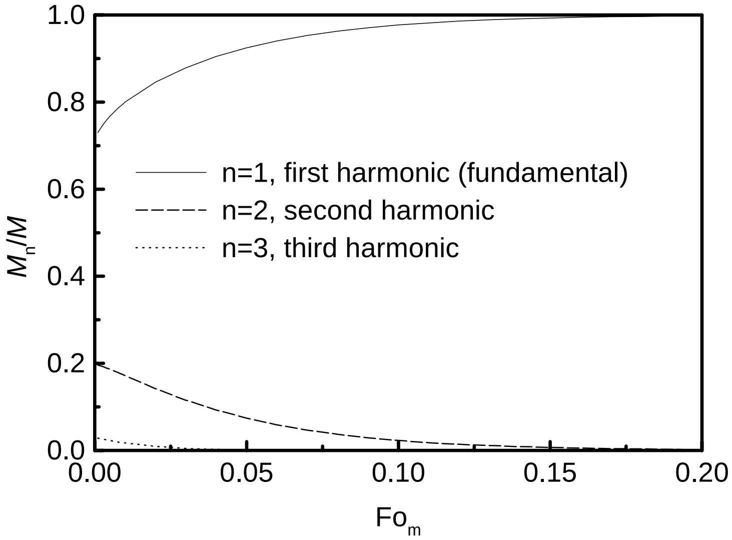


Figure 1. Dynamics of distribution of moisture content on harmonical components in solution of the system (8)-(10), $Bi_m$=10.

Thus, since the certain moment of time it comes so-called regular regime at which for a finding of diffusion coefficient inside of grains with the prescribed accuracy it is possible to consider only the first harmonic. Figure 2 shows the dependence of beginning of regular regime for a sphere with variation of moisture content $M$ as function of $Fo_m$, $Bi_m$ criteria for various tolerances.

## 3. EXPERIMENTAL STUDY

### 3.1. Experimental equipment

Figure 3 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.

Thin-layer drying tests were conducted for soybean in the temperature range 45-110°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.

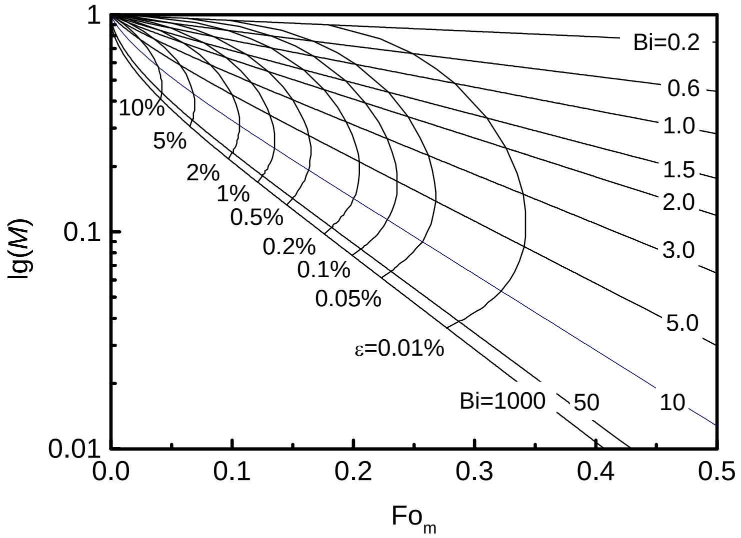


Figure 2. Start of regular regime for a sphere with variation of moisture content $M$ as function of $Fo_m$, $Bi_m$ criteria for various tolerances.

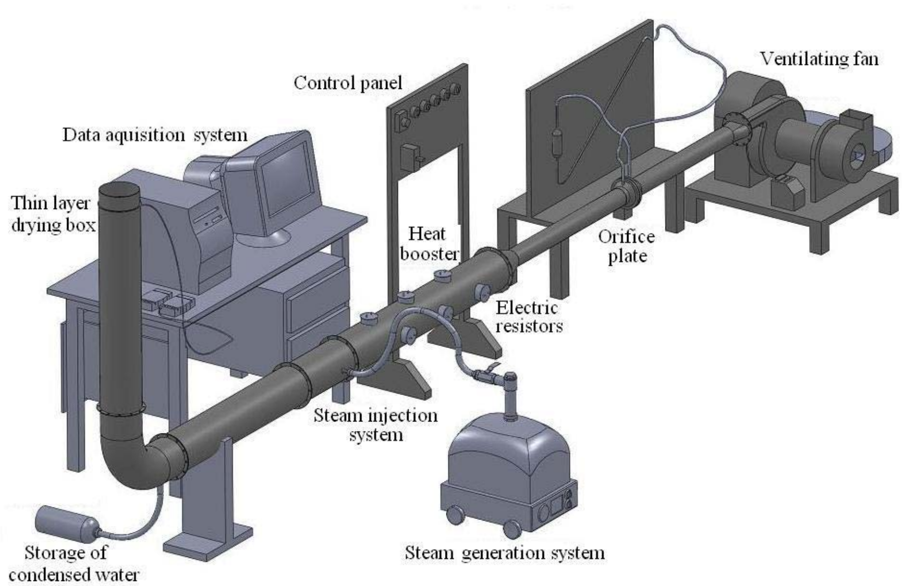


Figure 3. Experimental equipment.

### 3.3. Experimental results

In Figs. 4-9 some of the received experimental data on drying soybean dynamics are presented. Satisfactory concordance between these data and Soares (1986) data, presented in Figs. 4 and 5, 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. With time this rate decreases and ceases to depend on initial grain moisture content (Fig. 6). With augmentation of temperature (Fig. 7) 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. 8). 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.

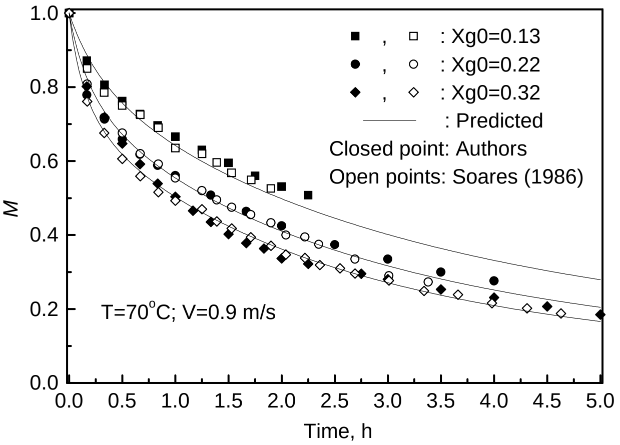


Figure 4. Soybean drying dynamics in a thin-layer at different initial grain moisture contents: T=70ºC.

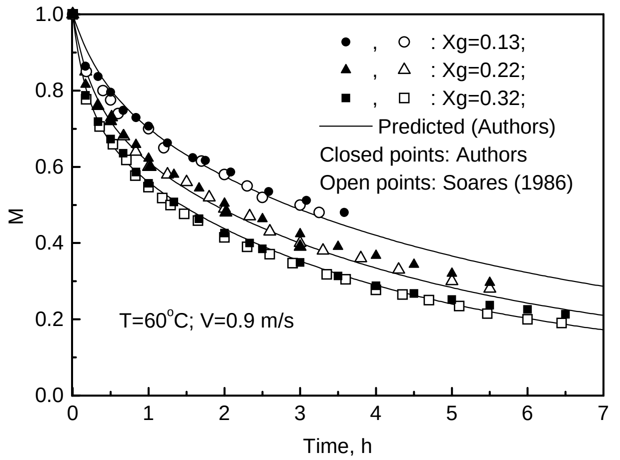


Figure 5. Soybean drying dynamics in a thin-layer at different initial grain moisture contents: T=60ºC.

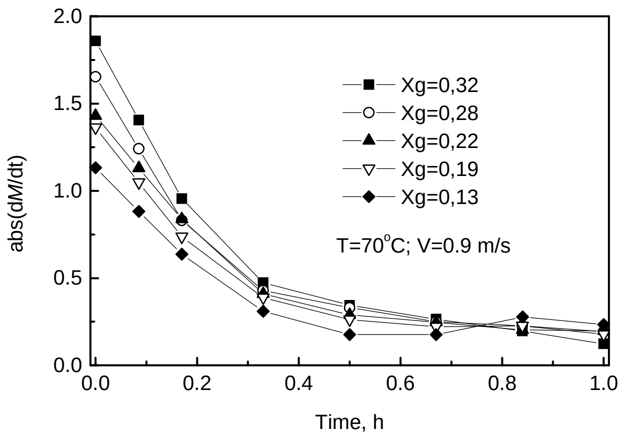


Figure 6. Dynamics of absolute drying rate variation in a thin layer at different initial grain moisture contents

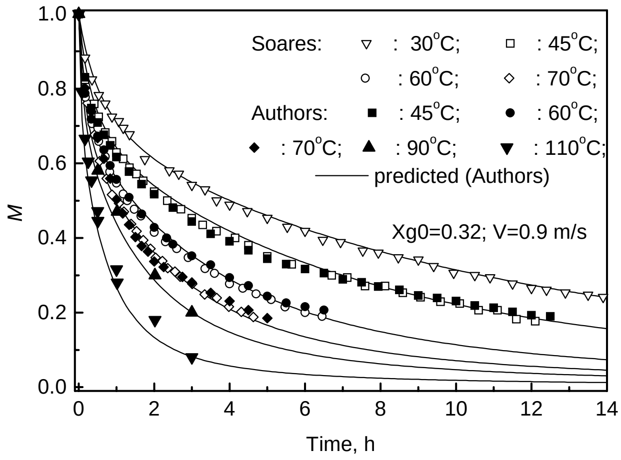


Figure 7. Temperature influence on soybean drying dynamics.

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 9 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).

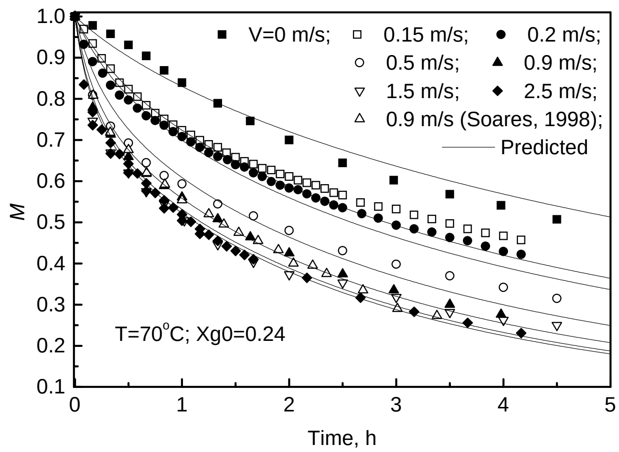


Figure 8. Velocity influence on soybean drying dynamics.

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.

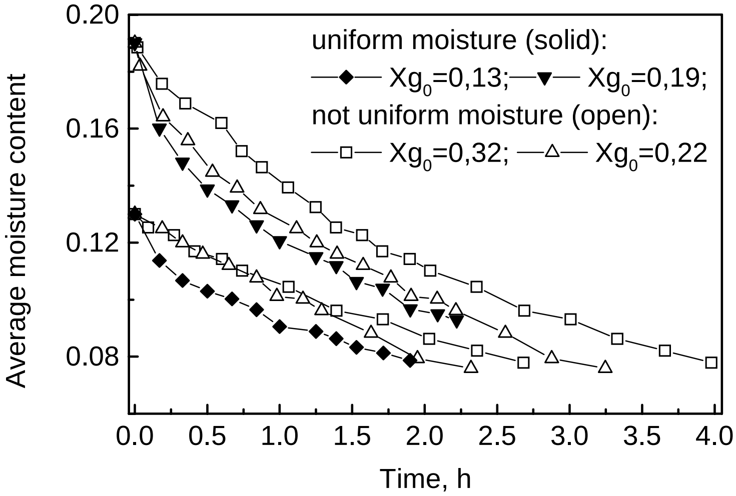


Figure 9. Thin- layer drying dynamics for "uniform" and "non uniform" initial distribution of moisture inside of grain.

## 4. TWO-COMPARTMENT MODEL FOR SOYBEAN THIN-LAYER DRYING

As experimental study showed, the diffusion coefficient has variable value in a radial direction. Therefore in this work the two-layer grain model has been chosen. The mathematical model is presented by system of two ordinary differential equations:

$$\begin{cases} \dfrac{dX_1}{dt} = -k_1\left(X_1 - X_2\right); \\ \dfrac{dX_2}{dt} = -k_1\left(X_2 - X_1\right) - q \cdot k_2\left(X_2 - X_e\right)^n \end{cases} \tag{14}$$

where $X_1$ and $X_2$ are average concentrations in 1th and 2nd compartments respectively, $k_1$ and $k_2$ are proportionality coefficients, $t$ is time in $s$, $n$ is constant, $q$ is factor related with velocity influence.

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 relative grain humidity, the systems can be presented in form:

$$\begin{cases} \dfrac{dM_1}{dt} = -k_1\left(M_1 - M_2\right); \\ \dfrac{dM_2}{dt} = -k_1\left(M_2 - M_1\right) - q \cdot k_2\left(X_{g0} - X_e\right)^{n-1} M_2^n \end{cases} \tag{15}$$

Second equation in system (15) presents the influence of drying rate from: a) initial moisture content $X_{g0}$ and, b) air humidity through equilibrium moisture content $X_e$. Applying the inverse problem method, the coefficients $k_1$ and $k_2$ were obtained for different initial moisture contents and temperatures at same velocity V=0.9 m/s ($q$=1). As experimental data show (Figs. 10 and 11) 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:

$$q = \frac{2.3306}{1 + e^{-2V}} - 1 \tag{16}$$

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

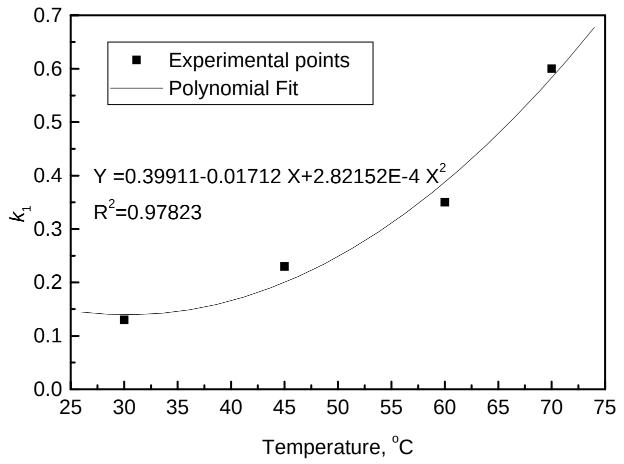


Figure 10. Dependence of coefficient $k_1$ from drying temperature.

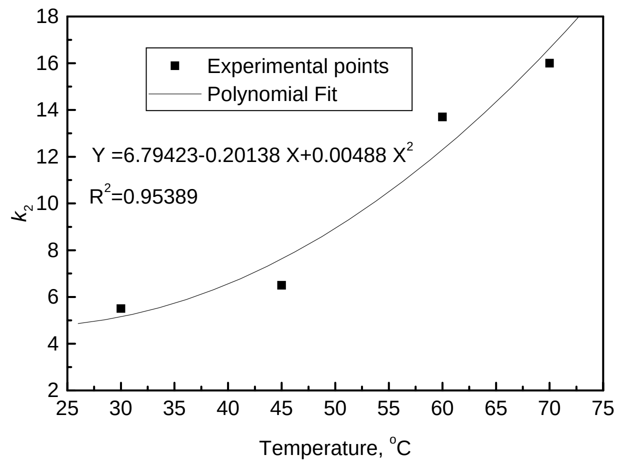


Figure 11. Dependence of coefficient $k_2$ from drying temperature.

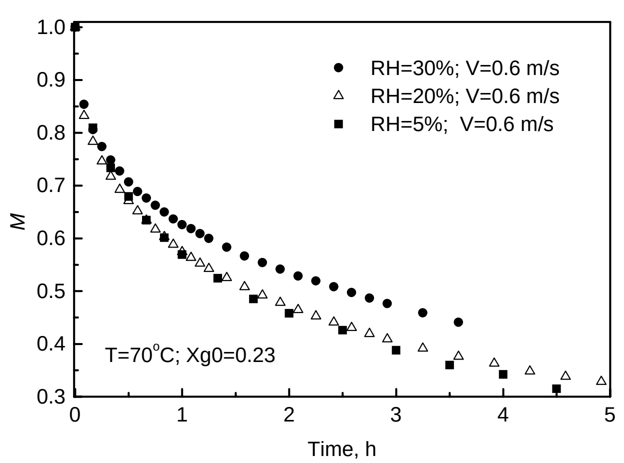


Figure 12. Influence of air relative humidity on thin-layer drying.

The continue curves in Figs. 4, 5, 7 and 8 present simulation by proposed model. Compartment volumes were assumed equals and $n$=2.

Figure 12 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 $X_e$. In spite of correct qualitative direction of this influence, its quantitative estimation must be improved.

## 5. CONCLUSION

It was studied the drying dynamics in soybean thin-layer for the temperature range 45-110$^o$C, velocity range 0-3 m/s, grain moisture content 13-32% with variation of air relative humidity (10-50%). Experimental data showed that the rate of influence of these parameters on drying dynamics 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 simulate soybean thin-layer drying dynamics the two-layer grain model has been chosen considering the soybean seed composed by two compartments with different diffusion coefficients. The mathematical model is presented by system of two ordinary differential equations. The simulation and experimental data showed satisfactory concordance.

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