

## **Numerical simulation to describe the soybean *Glycine max (L.)* drying process: Influence of air velocity, temperature and initial moisture content**

Camila Nicola Boeri<sup>1</sup>, Oleg Khatchatourian<sup>2</sup>

<sup>1</sup> University of Aveiro – Department of Mechanical Engineering, Campus Universitário de Santiago - Aveiro – Portugal

<sup>2</sup> Unijuí - Department of Physics, Statistics and Mathematics, Ijuí, Brazil  
<sup>1</sup>camilaboeri@ua.pt

**Abstract.** The production of soybean requires that the product is collected healthy and in advance, to minimize losses caused by the attack in the field of insects, diseases and microorganisms. Therefore and due to high moisture content at harvest, drying is one of the operations of primary importance among the techniques involved in the conservation of desirable qualities of products of plant origin. The objective of this work is to obtain the drying curves of soya, in the range of drying air temperature between 45 and 90°C, for the initial moisture content between 0.13 and 0.32 and drying air velocity of 0, 0.5, 0.9, 1.5 and 2.5m/s to determine the influence of these parameters in the process. The experimental phase was performed using a prototype of which was a hair metal tube with 0.15m in diameter, insulated throughout its surface with glass wool and canvas. The air was heated by six electrical resistance with power of 600W, while the temperature was controlled with the aid of thermocouples connected to the drying equipment. Were also performed numerical simulations, where the mathematical model used was proposed by Khatchatourian [1], and this search has changed the equation that describes the flow of mass, it is entering the parameters of air velocity and initial moisture content, obtaining a good agreement between experimental and simulated data. Was observed that the drying air velocity presents significant influence on the process, there is an increased withdrawal of water during the first hours of drying. Note that the influence of air temperature on the rate of drying is higher at the beginning of the experiment, reducing the processing time. The higher the temperature and airflow, the greater the drying rate and lower the total time of exposure to heated air.

**Keywords:** soybean, drying, simulation, mathematical model.

### **1 Introduction**

The production of soybean requires that the product is collected healthy and in advance, to minimize losses caused by insects attach in the field, diseases and

microorganisms. This way and due to high moisture content at harvest, drying is one of the primary importance operation among the techniques involved in the conservation of desirable qualities of products of vegetable origin.

The drying of agricultural products can be defined as a process of simultaneous heat and mass transfer between the product and air-drying, which consists in removal of excessive moisture in the interior of the grain through evaporation, usually caused by forced and heated air convection.

Several parameters influence the time required to reduce the seed moisture level for safe storage. The main factors to consider are: temperature, relative humidity and air flow, initial and final moisture content and type of grain.

Felipe and Barrozo (2003) studied the simultaneous heat and mass transfer between air and soybean seeds in a concurrent moving bed dryer, based on the application of a two-phase model to the drying process. The numerical solution of the model is obtained by using a computational code based on BDF methods (Backwards Differentials Formulas). The experimental data of air humidity and temperature and of seed moisture content and temperature at the dryer outlet are compared to the simulated values, showing a good agreement. This work also analyzed the effect of the main process variables (drying air temperature, air relative humidity, air velocity and solids flow rate) on the soybean seeds quality during drying. Empirical equations fitted to the experimental data are proposed for predicting the soybean seed quality (germination, vigor and fissures) as a function of the investigated variables.

A two-dimensional spouted bed dryer was investigated by Wiriyaumpaiwong, Soponronnarit and Prachayawarakorn (2003). The experimental results have shown that the drying kinetics of soybean in a two-dimensional spouted bed dryer are of the form described in the thin layer drying. The expression for the model parameter in Newton's law of cooling equation accounting for the moisture contents and inlet air temperatures was developed. The initial moisture content and inlet air temperature conditions cause cracks in the kernels. The strong collision between kernels and deflector because of high superficial velocity leads to high percentage of broken soybeans in the spout region. However, the velocity of 15.9 m/s can reduce the breakage below 5%. The inactivation of urease at low-to-moderate moisture content is suitably described by the first order kinetics. The modified Monod equation is applied when the moisture content is higher than 26% dry basis due to the inhibitory effect of water content on the inactivation rate. To complete urease inactivation and maintain protein quality, the temperatures of 150°C should be used.

Sangkram and Noomhorm (2002) made a comparative study of soybean drying was carried out between one-stage and two-stage (high-low temperature) drying with shade drying as control. In one-stage drying, the beans were dried at 80, 100, 120, and 140°C, respectively while in two-stage drying, beans were dried at 100, 120, and 140°C in the first stage followed by 80°C in the second stage. The evaluation values after drying showed that high drying temperature caused high skin cracks of the beans. Qualities of extracted crude oil characterized by free fatty acids (FFA), peroxide value (PV), phospholipids (PL) and nonhydratable phospholipids (NHP) were not significantly effected at  $p < 0.05$  by different drying methods but NHP had the increasing trend with the drying temperature and two-stage dried beans tended to

have NHP higher than one-stage dried beans. The quality of protein in meal determined in terms of protein dispersibility index (PDI) was less than 15% when drying temperature in one-stage drying was higher than 80°C and when the temperature at the first stage of two-stage drying was higher than 100°C. Drying temperature also had the effect on the quality of lecithin when considered in term of the acetone insoluble value (AI). Free fatty acids of extracted crude oil increased when dried beans were stored for two months at 35°C while PL decreased especially in the first month of storage. However, the AI value of lecithin did not change with time.

The simultaneous heat and mass transfer between air and soybean seeds in countercurrent and concurrent moving bed dryers by simulation was analyzed by Barrozo et al. (1998). The technique chosen was based on modeling from mass and energy conservation equations for the fluid and particulate phases. The equilibrium, heat transfer and mass transfer equations were taken from specific studies. The equation representing drying kinetics was obtained by means of a thin-layer study, whereas the equilibrium equations was chosen from rival model discrimination, based on nonlinearity measures. Hence, the model parameters were defined by the respective studies. The profiles for temperature and humidity of the fluid and the temperature and moisture of the seeds were obtained by numerical solution of the model. This model consisted of ordinary differential equations and the solution was obtained by a specific code.

According to the above, the objective of this work was to obtain the curves of soybeans drying in thin layer with temperatures of the drying air of 45, 60, 70, 80 and 90°C for initial moisture contents 0.13, 0.19, 0.22, 0.28 and 0.32 (dry basis) and drying air velocities equal to 0m/s, 0.5m/s, 0.9m/s, 1.5m/s and 2.5m/s, determine the influence of moisture content, temperature and air velocity on the drying of soybean by conducting experiments and numerical simulations using the proposed mathematical model, comparing the simulated results with experimental data.

## **2 Materials and methods**

### **2.1 Experimental installation**

This equipment can be divided into two systems: one that generates the flow of air and another that carries out the drying. The first consists of a centrifugal fan, ducts and a hole plate to measure the flow of air. The second is made by heating the air, the drying cylinder and equipment to measure air temperature. To heat the air, it was used six electrical resistors with power 600W. To control the temperature of the drying air, a thermocouple was installed inside the drying chamber containing the mass of soybean. This camera was metallic and cylindrical, with diameter of 0.15 m, coupled to the system of ventilation / heating air, and had a screen which was put the mass of grains to be submitted to the flow. The thickness of the layer of grain was about 7 mm or two grains.

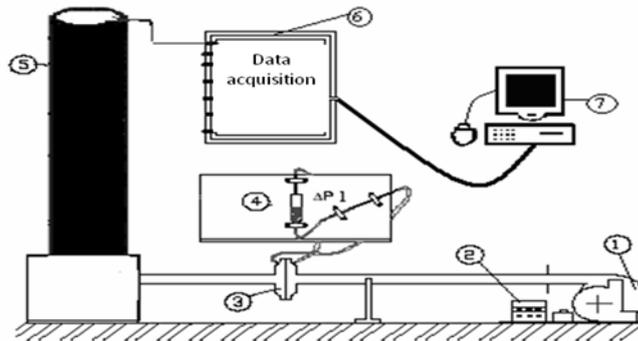


Fig. 1: Representation of drying equipment

## 2.2 Drying experiments

Initially, it was determined the initial moisture content of grain through the direct method, following the standards set by the Ministry of Agriculture, submitting a mass of 15g of grains in an oven at a temperature of 105°C for 24 hours. The measures of mass were made using a digital analytical balance with precision  $10^{-3}$ .

After measuring the moisture content, the soybean was placed in plastic packaging, hermetically sealed, containing a mass of 200g of grains in each sample. The seal was made with the aid of a machine for seal. After sealed, the samples were put in the refrigerator at a temperature of 4°C in order to retain its moisture content. Twenty-four hours before starting the process of drying, the sample was removed from the refrigerator and left in contact with ambient air. After this time, was made a pre-heating for five minutes in the oven, with the same temperature which would be carried out the drying. The mass of grains was measured again when it was removed put the oven.

Then, the sample was placed in a drying chamber and it was started the counting of time. After the desired time for drying, the mass was again measured and replaced in the dryer, this procedure is repeated for all desired times. For this, the mass of grains was around 20s out of the dryer, the necessary time to remove the sample, to take note the measurement, record the extent and return it to the dryer. The drying interval was increased by 10 minutes in the first hour, 20 minutes in the second hour and the third hour by 30 minutes. The experiment was terminated when the moisture content was around 8% (dry basis), which caused the drying time was not the same in all experiments.

The equilibrium moisture content of soybeans was calculated for each condition of relative humidity and temperature of drying, according Dalpasquale (1981):

$$X_e = \frac{3.962 \cdot HR_s^{0.4919}}{100 \cdot \ln(T_s)} \quad (1)$$

where HRS is the relative humidity of the drying air (percentage) and  $T_s$  is the temperature of the drying air ( $^{\circ}\text{C}$ ).

Having the initial moisture contents, of equilibrium and the instantaneous moisture mass of the grains, was obtained the reason values of humidity for each drying process, given by the following expression:

$$RU = \frac{X - X_e}{X_0 - X_e} \quad (2)$$

where  $X$  is the moisture content of the product (dry basis),  $X_e$  is the equilibrium moisture content and  $X_0$  is the initial moisture content.

### 2.3 Mathematical model

The mathematical model used in this research is based on the proposed by Khatchatourian et al. (2003). This model was adapted to describe the drying of soybean in a fixed bed dryer and is composed of a system of four partial differential equations, hyperbolic, quasi-linear, coupled, where the equations look at the exchange of heat and mass between air and grain. However, despite satisfactorily describe the drying curves for the influence of air temperature, this model does not take into consideration the influence of air velocity and the initial moisture content of grain in the process. Thus, in order to consider the influence of the air velocity of the drying and the initial moisture content of grain, will be done an adjustment of the coefficient of mass transfer during the drying process, modifying it in the model proposed by Khatchatourian (2003).

Taking into account the considerations made in the formulation of the problem of drying of soybeans in a fixed bed dryer, the mathematical model consisting by the system of partial differential equations obtained the balance sheets of energy and mass is formed by the following equations: equation conservation of water in the air, equation of conservation of energy in the air, equation of conservation of water on grain and equation of energy conservation in relation to the grain. There are the following equations: density of mass flow and density of the flow of heat.

**Equation of conservation of water in the air:** This equation determines the variation of moisture content of air at different dryer internal points.

$$\frac{\partial Y}{\partial t} + v_a \frac{\partial Y}{\partial z} = \frac{a_{sv} \varphi_m (1-\varepsilon)}{\varepsilon \rho_a} \quad (3)$$

where  $Y$  is the moisture content of air,  $v$  is velocity of air,  $a_{sv}$  is the reason between the surface area and volume of grain,  $\varepsilon$  is the porosity,  $\rho_a$  is the density of the air and  $\Phi_m$  is the density of the flow of mass.

**Equation of energy conservation for the air:** This equation determines the energy transferred by air to the grains.

$$\frac{\partial T_a}{\partial t} + v_a \frac{\partial T_a}{\partial z} = \frac{a_{sv}(1-\varepsilon)}{\varepsilon \rho_a (C_{pa} + Y C_{pv})} [\varphi_m C_{pv} (T_g - T_a) + \varphi_h] \quad (4)$$

where  $T_a$  is air temperature,  $C_{pa}$  is the specific heat of air at constant pressure,  $C_{pv}$  is the specific heat of water vapor pressure constant,  $T_g$  is the temperature of the grain and  $\Phi_h$  is the density of the flow of heat.

**Equation of conservation of water in grain:** This equation determines the variation of moisture content within the grain.

$$\frac{\partial X}{\partial t} = - \frac{a_{sv} \varphi_m}{\rho_g} \quad (5)$$

**Equation of conservation of energy in the grain:** This equation determines the energy to heat the grain and to evaporate the water.

$$\frac{\partial T_g}{\partial t} = - \frac{a_{sv} \{ \varphi_h + \varphi_m [H_v + T_g (C_{pv} - C_{pw})] \}}{\rho_g (C_{pg} + X C_{pw})} \quad (6)$$

where  $T_g$  is the temperature of the grain,  $H_v$  is the latent heat of vaporization,  $C_{pw}$  is the specific heat of water by pressure and the  $C_{pg}$  is the specific heat of grain.

**Density of mass flow:** With the heating of the grain, and the consequent increase of pressure inside, he breaks the equilibrium moisture content and water in vapor form, tends to leave. The quantity of the water in the form of steam, which crosses the surface of the grain per unit area and per unit of time is what determines the density of mass flow. Khatchatourian (2003), using the relations of Chilton-Colburn (SISSON, 1988), set the equation of mass flow, taking into account the influence of the drying air velocity, obtaining the following relationship:

$$\varphi_m = \sqrt{\frac{v_a}{v_0}} M_1(T) \cdot e^{-\sqrt{M_2(T) + M_3(T) \cdot \ln(X - X_e)}} \quad (7)$$

where  $\Phi_m$  is the density of mass flow and  $M_1(T) = K_1(X_0 - X_e)$ ;  $M_2(T) = K_2 - K_3 \cdot \ln(X_0 - X_e)$ ;  $M_3(T) = K_3$  where  $K_1$ ,  $K_2$  and  $K_3$  are temperature functions.

**Density of heat flux:** It is the amount of heat that passes through the surface of the grain per unit time and per unit area. The transfer of heat in the drying occurs predominantly by forced convection between the air-drying and the surface of the grains. According to the law of Newton-Richmann for convective heat transfer, the flow of heat is proportional to the temperature difference between air and grain, given by:

$$\varphi_h = h(T_g - T_a) \quad (8)$$

where  $\Phi_h$  is the density of heat flux,  $h$  is the coefficient of heat transmission,  $T_g$  is the temperature of the grain and  $T_a$  is air temperature.

Khatchaturian (2003) from the heat transfer coefficients proposed by Loncin, used by Courtois and Lasseran (1993) and made using same analogy for mass transfer found the following equation for the of  $h$ :

$$h = \sqrt{\frac{v_a}{v_0} (-19.718 + 0.2576T_g + 379.41Y)} \quad (9)$$

**Modification of the model:** The model described above was modified to adjust the influence of the air velocity of drying and the initial moisture content of grain. The change took place in the equation concerning the flow of mass given by Eq. (7). Thus, the mass flow will be described by:

$$\varphi_{m\epsilon} = (a \cdot v + b) \cdot \frac{X^c}{X_0} \cdot \left( M_1(T) \cdot e^{-\sqrt{M_2(T)+M_3(T) \cdot \ln(X-X_2)}} \right) \quad (10)$$

where the coefficients  $a$ ,  $b$  and  $c$  were obtained by the method of least squares using the experimental data to minimize the functional.

Thus, the equation can be written as:

$$\varphi_{m\epsilon} = (0.85 \cdot v + 0.15) \cdot \frac{X^{0.856}}{X_0} \cdot \left( M_1(T) \cdot e^{-\sqrt{M_2(T)+M_3(T) \cdot \ln(X-X_2)}} \right) \quad (11)$$

### 3 Results and discussion

#### 3.1 Influence of air velocity on drying

Figures 2 and 3 show the curves of drying depending on the air velocity, kept at constant temperature at 45°C for various moisture contents, where the discrete curves represent the experimental date and the continuous are the simulated results. There is

an increased withdraw of water during the first hours of drying. As Hall (1980), after the first hours, the drying rate had decreased, due to internal transport of water to be lower than the rate of evaporation, so the heat transfer is not offset by the transfer of mass and therefore there is increase the temperature of the product.

Figures 4 and 5 show the drying curves for others depending on the air velocity to the other levels of measured temperatures - 70°C and 90°C -, which can be observed similar behavior in all cases, as described above.

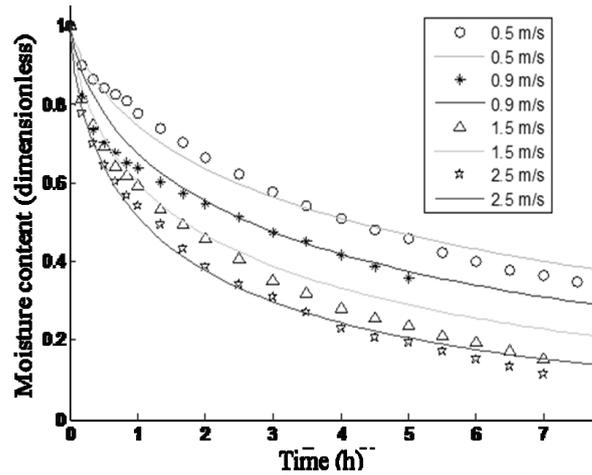


Fig. 1: Influence of air velocity.  $T_s=45^\circ\text{C}$ ,  $X_0=0.28$

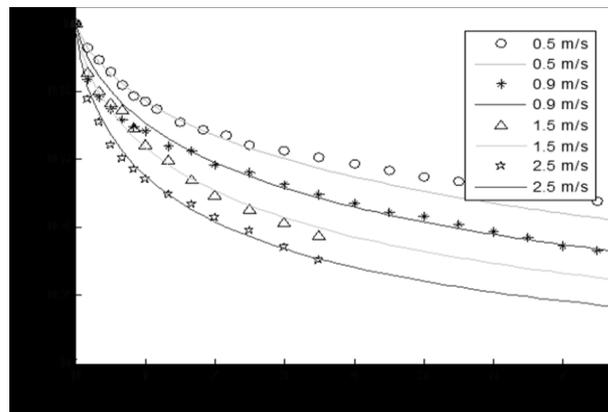


Fig. 3: Influence of air velocity.  $T_s=45^\circ\text{C}$ ,  $X_0=0.22$

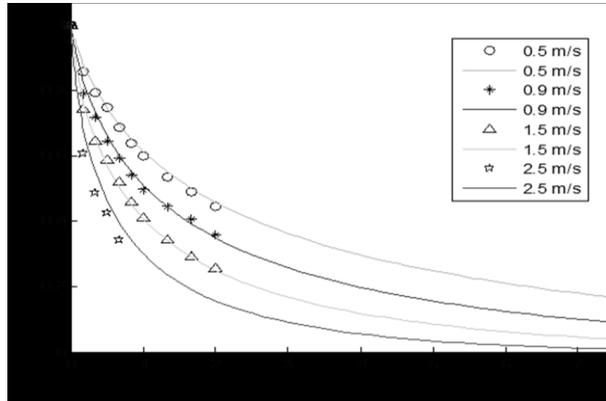


Fig. 4: Influence of air velocity.  $T_s = 90^\circ\text{C}$ ,  $X_0 = 0.19$

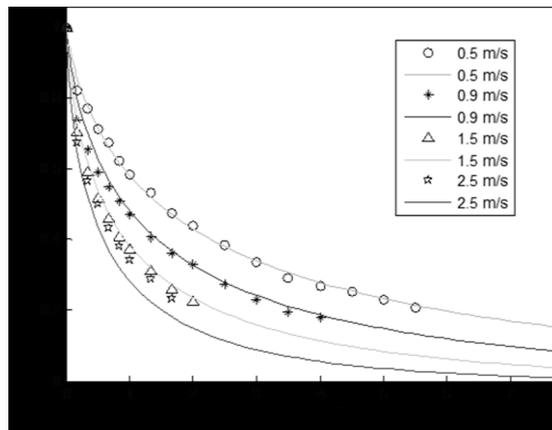


Fig. 5: Influence of air velocity.  $T_s = 70^\circ\text{C}$ ,  $X_0 = 0.32$

### 3.2 Influence of temperature on drying

The Fig. 6 and Fig. 7 show the drying curves with air temperature influence. It is observed that the drying rate increased with increasing temperature, this is, it requires a shorter time of exposure of soybean to the heated air to reach the desired moisture content, due to increased availability of energy for the vaporization of water. This is

because raising the temperature increases the coefficient of diffusion of mass. There is also that at the beginning of drying, the evaporation of water is more pronounced, decreasing over time, becoming zero at the end of this. Here, the effects of mass transfer become negligible when the grains tend to attain the equilibrium moisture contents.

It was observed that the longer the drying occurred at 45°C, and the lowest at 90°C, with decreasing effect over time of drying as occur the increase in air temperature. This is caused due to the increased potential for drying due to the increase of air temperature, which means that there is decreasing relative humidity and drying.

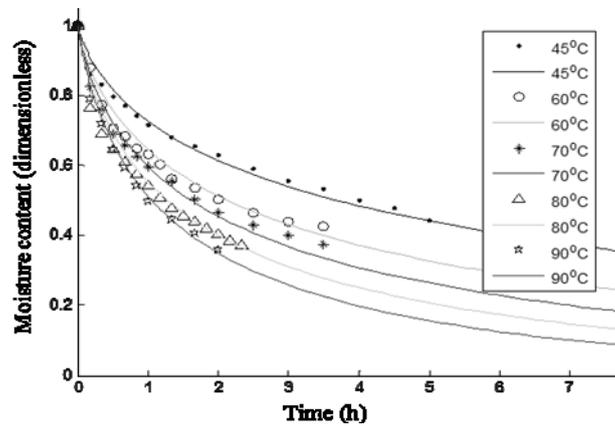


Fig. 6: Influence of air temperature.  $v=0.9$  m/s,  $X_0=0.19$

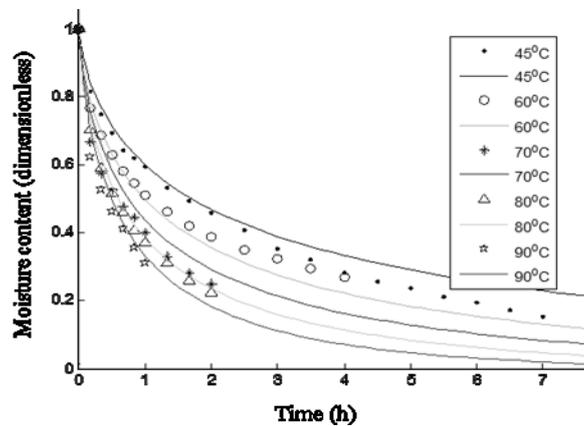


Fig. 7: Influence of air temperature.  $v=1.5$  m/s,  $X_0=0.28$

### 3.2 Influence of initial moisture content of grain

The curves of drying below indicate a variation of moisture faster for higher levels of humidity and slow drying to lower moisture contents, since the higher levels there is a larger gradient of moisture between the grain and air. Another factor is that when the grain has a high moisture content, much of this water is concentrated in the pores of the grains, and it's easier to release. Already low levels of humidity, concentration of water in the pores is smaller, the water left that is part of the composition of the molecules of the grains, which is more difficult to be released.

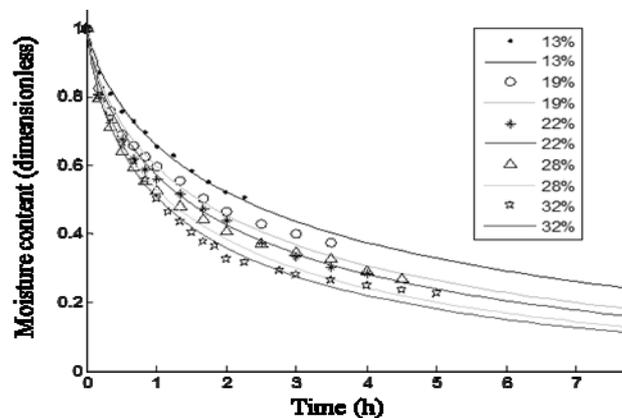


Fig. 8: Influence of initial moisture content of grain.  $v = 0.9$  m/s,  $T_s = 70^\circ\text{C}$

## 4 Conclusion

The experimental methodology used seemed to be appropriate to achieve the research objectives. This study verify that the drying is significantly affected by the parameters velocity and air temperature of the drying and initial moisture content of soybean.

Can be observed that the air velocity of the drying presents significant influence on the process, noticing a bigger removal of water during the first hours of drying.

Realize that the dynamics of drying grain of soybean show a clear dependence with the air velocity and temperature of drying, this feature is present in the most agricultural. Note that the influence of air temperature on the rate of drying is higher at the beginning of the experiment, reducing with the processing time.

What about mathematical model used in this study, the proposed amendment has summed appropriate since it was found that the drying air velocity is a very important parameter, which is indispensable in the mathematical model, as showed the analysis carried out.

## References

1. Barrozo, M.A.S., Murata V.V., Costa, S.M.: The drying of soybean seeds in countercurrent and concurrent moving bed dryers. *Drying Technology*, 16 (9), 2033 – 2047 (1998).
2. Brooker, D.B., Bakker-Arkema, F.W., Hall, C.W.: *Drying cereal grains*. The Avi Publishing Company, Westport (1974).
3. Courtois, F., Lasseran, J.C.: A CAD Software to improve the heat energy efficiency of mixed-flow maize dryers. CESA/FAO, Proc. Latin American Technical Meeting of Grain Drying a Storage, 18-22 (1993).
4. Dalpasquale, V.A.: *Drying of soybeans in continuous-flow dryers and fixed-bed drying systems*. Tese (Ph.D), Michigan State University, Michigan (1981).
5. Felipe, C.A.S., Barrozo, M.A.S.: Drying of soybean seeds in a concurrent moving bed: heat and mass transfer and quality analysis. *Drying Technology*, 21(3), 439- 456 (2003).
6. Hall, C.W.: *Drying and storage of agricultural crops*. Westport: AVI Publishing Company (1980).
7. Khatchaturian, O., Borges, P.A.P., Vielmo, H.A.: Simulation of soy grains drying dynamics in camera of fixed bed. Proc. XVII COBEM, International Congress of Mechanical Engineering, Anais. CD-ROM (2003).
8. Ministério da Agricultura e Reforma Agrária do Brasil, “Regras para análise de sementes”. Brasília: SNDA/DNDV/CLAV, 365 p. (1992).
9. Queiroz, D.M. *et al.*: Modelos matemáticos de simulação de secagem de grão. Viçosa: Centreinar (1985).
10. Sangkram, U., Noomhorm, A.: The effect of drying and storage of soybean on the quality of bean, oil, and lecithin production. *Drying Technology*, 20 (10), 2041 – 2054 (2002).
11. Wiriyaumpaiwong, S., Soponronnarit, S., Prachayawarakorn, S.: Soybean drying by two-dimensional spouted be. *Drying Technology*, 21(9), 1735 – 1757, (2003)