SIMULATION OF SOY GRAINS DRYING DYNAMICS IN CAMERA OF FIXED BED

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Abstract. *The proposed work is a stage to elaborate a software for the drying process optimization of continuous mixed flow dryers. The mathematical model consists of a system of four partial differential equations, that describe the heating and the grain humidity reduction, the air temperature fall and the air humidity increase in the considered conditions. To determine the mass and heat flow intensity for thin layer the experimental data were used. It was developed an equipment to obtain the grains drying curves in fixed-bed dryer, in order to identify the model. The explicit and implicit finite-difference methods were used (for instance, methods of MacCormack, Beam and Warming, Crank-Nicholson, etc.) for resolution of the hyperbolic system of the coupled quasi-linear partial differential equations. For convergence analysis the Neumann's method (without consideration of the boundary conditions) and matrix method (considering the boundary conditions) were used. It was shown that even for the implicit schemes with absolute stability, a maximum value of the Courant-Friedrichs-Lewy number exists, starting from which a numerical oscillation appears.*
The analysis of the results allowed to recommend the most appropriate method for each type of the problem. The comparison of the experimental results and the numerical simulations of the drying dynamics showed a good coincidence.

Keywords*:* *drying, numerical methods, mass and heat transfer*

1. Introduction

The soy culture has a strong participation in the economy of the northwest of the Rio Grande Do Sul state of Brazil. In each one of the production stage, since the planting up to the warehousing, a significant grain losses occur in stage of commercialization. The losses vary from region to region, adopted work routine, harvest techniques, machines, drying and warehousing kinds. For Brooker et al. (1982), the losses in the warehousing are in order of 4,5%. These losses occur because of the mechanic damages during the handling and deposit. The insects attack is responsible for the losses of 1 to 3%. Considering the harvest of the Rio Grande Do Sul state in 1994/1995, that was of 6 millions of tons, the economy of the state wouldn't count with something around 25,5 millions US dollars. Because of the characteristic climate of the Rio Grande Do Sul state when the soy bean harvest time arrives, the drying process becomes essential, in order that the product can be stored decreasing the losses because of the attack of fungus and insects. Therefore, the physics phenomena knowledge of drying process and efficient proceeding development, with low cost and minimum losses, are required in the activity of drying projects. In the northwest of the Rio Grande Do Sul state there are industries that produce dryers like "tower", a kind of dryer with mixed flux and metallic cylinder with aeration of the grain mass. These industries have more than 40 years of experience and improve their products, using physical models. The mathematical modeling, recently, have shown a powerful aid technique in the project activity.

The research in the mathematical modeling of grain drying process has already more than 50 years. Theoretical models (Luikov, 1966), empiric models, (Thompson et al., 1968), semi-empiric models, (Lewis, 1921; Nellist and O'Callaghan, 1971; Hendersen, 1974) were proposed to describe the drying process in thin layer. To describe the behavior of the air humidity and temperature and of the grain humidity and temperature in a large layer many models had been proposed for different flow kinds: fixed bed, cross-flow, counter-flow and concurrent-flow (Law and Parry, 1985; Bakker-Arkema et al., 1967; Brooker et al., 1982). To obtain more precise results for real drying, other searchers (Moreira and Bakker-Arkema, 1990, França et al., 1994; Souza and Ferreira, 1996), have created models with less simplifications and, mathematically, more complex, making modifications in the models of Thompson et al. (1968) and Brooker et al. (1982). Courtois et al., (1991), for drying of corn grains, proposed an one-dimensional model, considering the grain compound by three compartment and added an equation over the grain' s quality.

In this work, the model of Courtois et al. (1991) was modified to adapt for the soy fixed bed drying. The mass and heat fluxes were calculated, using experimental relationships in thin layer. The flow velocity influence on the heat and mass fluxes were also tested. To optimize the software performance, the Crank-Nickolson and MacCormack methods were analyzed.

2. Nomenclature

- a - ratio of grain surface area to grain volume, m^{-1};
- A_g - grain surface area, m^2;
- C_{pa} -specific heat of dry air, $J.kg^{-1}K^{-1}$;
- C_{pg} -specific heat of dry grain, $J.kg^{-1}K^{-1}$;
- C_{pv} -specific heat of water vapor, $J.kg^{-1}K^{-1}$;
- C_{pw} -specific heat of liquid water, $J.kg^{-1}K^{-1}$;
- H_v - latent heat of water vaporization, $J.kg^{-1}$;
- t - time, s;
- W_a -air velocity, m/s;
- W_g -grain velocity, m/s;
- X - grain moisture content, kg water/kg dry grain;
- Y - air absolute humidity in dryer, kg water/kg dry air;
- z - coordinate along air-flow axis, m;
- Φ_h - heat flux between air and grain, $W.m^{-2}$;
- Φ_m - mass flux between air and grain, $kg.m^{-2}.s^{-1}$;
- ε - porosity factor, m^3 pores/m^3 total volume;
- ρ_a -density of dry air, kg/m^3;
- ρ_g - density of grain dry matter, kg/m^3.

3. Mathematical model

The grain drying model utilized in this work is based on the models developed in Courtois (1991) and Khatchatourian et al. (1999). In the beginning, the model is developing for grain drying in fixed bed. The principal suppositions are the following ones:

1- The volume of grain contraction is neglected.
2- The temperature gradient inside the grains are neglected.
3- The heat conduction of particle to particle is neglected.
4- The air flux is uniform.
5- The heat transference by the walls is neglected.
6- The humid air and grain heat capacities are constant, during a short period of time.
7- The drying equations for thin layer are gotten from experimental data.

For these conditions, the grains drying problem in a thick layer can be described by the system of four quasi-linear partial differential equations:

$$\frac{\partial X}{\partial t} + W_g \frac{\partial X}{\partial z} = -\frac{\Phi_m a}{\rho_g} \tag{1}$$

$$\frac{\partial T_g}{\partial t} + W_g \frac{\partial T_g}{\partial z} = \frac{-a\,(\Phi_m H_v + \Phi_h)}{\rho_g (C_{pg} + C_{pw} X)} \tag{2}$$

$$\frac{\partial Y}{\partial t} + W_a \frac{\partial Y}{\partial z} = \frac{a\,\Phi_m\,(1-\varepsilon)}{\varepsilon\,\rho_a} \tag{3}$$

$$\frac{\partial T_a}{\partial t} + W_a \frac{\partial T_a}{\partial z} = \frac{a(1-\varepsilon)}{\rho_a\,\varepsilon} \cdot \frac{\Phi_m C_{pv} (T_g - T_a) + \Phi_h}{C_{pa} + C_{pv} Y} \tag{4}$$

The following initial and boundary conditions were considered for the fixed bed problem (W_g=0):

$$T_a(0, z)= T_{g0}\,,\ \forall z \in (0, L];\quad T_g(0, z)= T_{g0},\quad \forall z \in [0, L];\quad T_a(t, 0)= T_{a0};\ \forall t\in [0, \infty);$$
$$Y(0,z)= Y_0\,,\quad \forall z \in (0, L];\quad Y(0,z)= Y_0,\quad \forall z \in (0, L];\quad X(0, z)=X_{g0},\ \forall z \in [0, L]. \tag{5}$$

To realize the numerical simulation, solving the system of Eqs. (1)-(4), it is necessary to know the dependence of the mass flux Φ_m and heat flux Φ_h on the main drying process parameters (the air humidity and temperature, the grain moisture content and temperature, the equilibrium moisture content, porosity factor, the air velocity, etc.).

4. Calculation of the mass flow density

The mass flux Φ_m is directly connected with the variation rate of the water mass in the grain:

$$\Phi_m = -\frac{\partial m_{wg}}{\partial t} \cdot \frac{1}{A_g} \tag{6}$$

The experimental curves, obtained by Soares (1986) for soy bean drying in thin layer, were analyzed. The analysis and treatment of these data (points in Fig. (4)) have shown that the dependence between the water mass flux and the water vapor concentration gradient is not linear, i.e., on the contrary, what the Fick diffusion law establishes. To find this dependence, the curves of soy beans drying dynamics in thin layer (experimental data of Soares (1986) for several temperatures) were represented in form:

$$RU = f\left(\frac{\partial RU}{\partial t}\right) \tag{7}$$

where: $RU=(X-X_e)/(X_0-X_e)$ is a relative grain humidity. Using the 2nd degree polynomial:

$$\ln(RU) = a.\ln^2\left(-\frac{\partial RU}{\partial t}\right) + b.\ln\left(-\frac{\partial RU}{\partial t}\right) + c \tag{8}$$

To the generalization of the experimental data, was obtained the function:

$$\frac{\partial RU}{\partial t} = -K_1 \cdot e^{-\sqrt{K_2 + K_3 \cdot \ln(RU)}} \tag{9}$$

where K_1, K_2 and K_3 are temperature functions. Denoting:

$$M_1 = K_1(X_0-X_e);\ M_2 = K_2-K_3.\ln(X_0-X_e);\ M_3 = K_3 \tag{10}$$

the water vapor mass flux of the soy bean to the ambient air can be written in this form:

$$\Phi_m = M_1(T).e^{-\sqrt{M_2(T)+M_3(T).\ln(X-X_e)}} . \frac{\rho_g}{a} \tag{11}$$

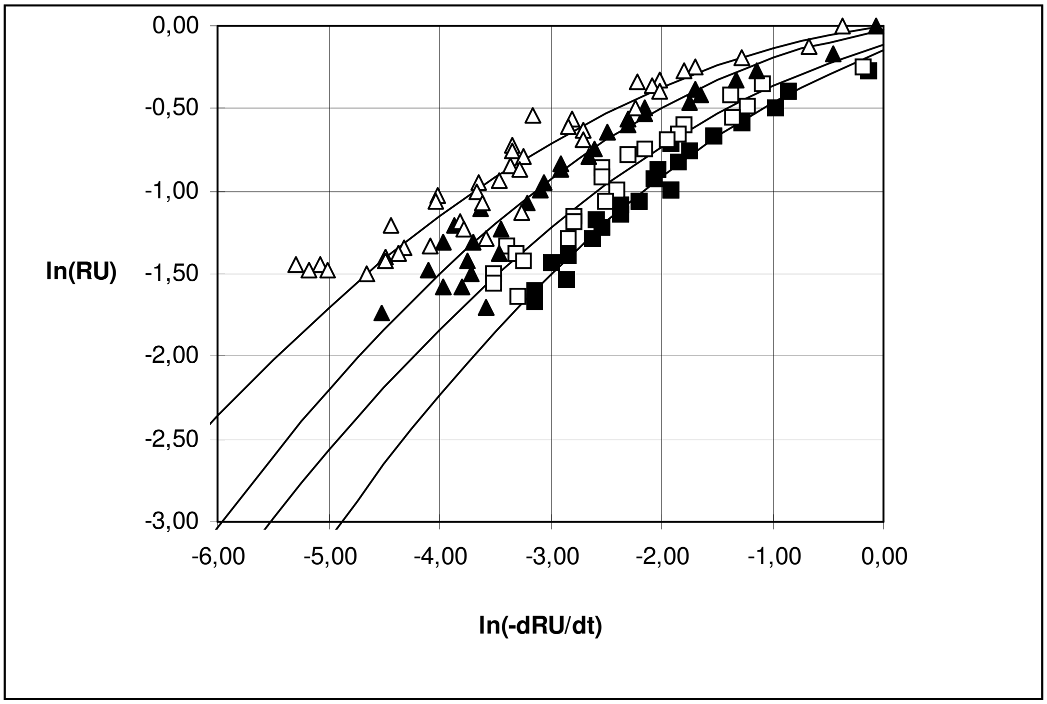

Figure 1. Relationship among drying rate in thin layer and relative grain moisture content: experimental data of Soares (1986) for thin layer (points) and predicted curves (authors): ■ 70^{0}C; □ 60^{0}C; ▲ 45^{0}C; Δ 30^{0}C; ——predicted.

5. Calculation of the flow heat density

The heat transfer in the drying process occurs, predominantly, by forced convection between the drying air and the grain surface. By the Newton-Richmann law for convective heat transfer, the heat flux is proportional to the temperature difference of air and grain, and physically, it is the quantity of energy (sensitive heat) transferred, in this case, from the air to the grain, per unit area and per unit time:

$$\Phi_h = h\,(T_g - T_a) \tag{12}$$

where: h is the heat transfer coefficient, Tg and Ta are the grain and the air temperatures, correspondingly.

To find the heat flux between the grain and the air, the heat transfer coefficient was calculated by the Eq. (13), presented by Loncin (1979), and applied by Courtois et al. (1991), for the corn drying model:

$$h = -19{,}718 + 0{,}2576 \cdot T_g + 379{,}41 \cdot Y \tag{13}$$

Using the relationships of Chilton-Colburn (Sissom and Pitts, 1988) for the airflow in packed bed, it was included the air velocity influence on the heat and mass flux:

$$h = \sqrt{W_a / W_0}.\left(-19{,}718 + 0{,}2576.T_g + 379{,}41.Y\right) \tag{14}$$

$$\Phi_m = \sqrt{W_a / W_0} \cdot M_1(T).e^{-\sqrt{M_2(T) + M_3(T).\ln(X - X_e)}} . \frac{\rho_g}{a} \tag{15}$$

6. Solution of the partial differential equations

The system (hyperbolic) of partial differential quasi-linear equations was rewritten in the matrix form:

$$\frac{\partial U}{\partial t} + C\frac{\partial U}{\partial z} = F(z, t, U) \tag{16}$$

where: $U=(X, T_g, Y, T_a)^T$.

To solve the system different methods were analyzed with the objective of choosing the best performance. The results of the calculations, made by two methods of the second order, are presented in this work: the MacCormack method (explicit of two steps), and the Crank-Nicholson method (implicit). It was admitted for the examined system that the satisfaction of the consistence and stability conditions are sufficient for the method convergence, in other words, it means that the Lax theorem, demonstrated for linear equations, can be also used for the considered case in this work.

7. MacCormack method

The method of MacCormack (1969) is generally used for the solution of partial differential nonlinear equations and may be considered as variant of Lax-Wendroff two steps method. The method was presented in this form:

predictor:

$$\overline{U_j^{n+1}} = U_j^n - C\frac{\Delta t}{\Delta z}\left(U_{j+1}^n - U_j^n\right) + \Delta t \cdot F_j^n \tag{17}$$

corrector:

$$U_j^{n+1} = \left[U_j^n + \overline{U_j^{n+1}} - C\frac{\Delta t}{\Delta z}\left(\overline{U_j^{n+1}} - \overline{U_{j-1}^{n+1}}\right) + \Delta t \cdot \overline{F_j^{n+1}}\right]/2 \tag{18}$$

The stability of this method, analyzed in this work by the Neumann method (not analyzing the boundary conditions), is conditional and is satisfied for values of Courant-Friedrichs-Lewy (CFL) number $\delta = c \cdot \Delta t / \Delta z$ in the interval: $0 < \delta \le 1$.

The truncation local error is of second order $0(\Delta z^2, \Delta t^2)$.

8. Implicit method centralized by time (Crank-Nicholson)

In order to decrease the limitations in choosing the integration step, it was also applied the centralized implicit scheme by time (Crank-Nicholson method), that was presented in form:

$$U_j^{n+1} - U_j^n + C\frac{\Delta t}{4\Delta z}\left(U_{j+1}^{n+1} + U_{j+1}^n - U_{j-1}^{n+1} - U_{j-1}^n\right) - \Delta t \cdot F_j^{n+1/2} = 0 \tag{19}$$

After applying of linearizing transformation for nonlinear term the scheme was presented in form:

$$T \cdot U^{n+1} = H \cdot U^n + G \tag{20}$$

The scheme is of second order and absolutely stable, but for each time step it is necessary to resolve the tridiagonal system of linear algebraic equations. For the stability analysis with the boundary conditions influence, the system of finite-difference equations was transformed in the matrix form:

$$U^{n+1} = BU^n + d \tag{21}$$

where B is the temporal step operator (transition matrix). For the initial and boundary conditions (5) in this work it was shown that largest eigenvalue of the transition matrix B is less than 1, i.e., $\max|\lambda(B)|<1$. It is the necessary and sufficient condition for the iterative process to be convergent.

The tridiagonal matrix T depends on the Courant-Friedrichs-Lewy number only. That is why for the resolution of system (20) it was applied L-U decomposition of the matrix T. If the temporal or spatial step was altered during the calculation, it was realized L-U decomposition again.

9. Equipment description

The realization of experiments, in this work, has as objective the verification of the mathematical model of soy grain drying in a fixed bedstead. The equipment is schematically shown in Fig. (2).

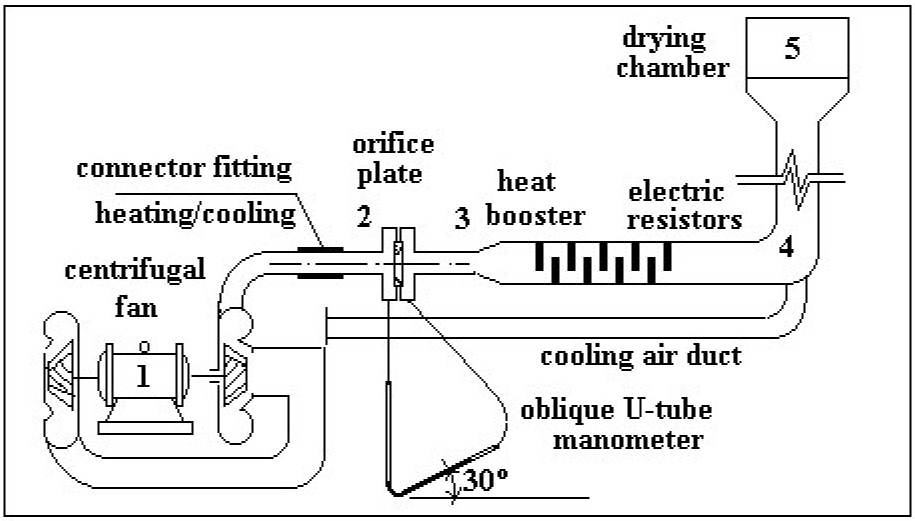

Figure 2. Sketch of the experimental equipment.

The equipment is composed by an electric motor (1) of ¾ of hp (552 W), with 3450 rotation per minute ($57{,}5\ s^{-1}$), that sets in motion two centrifugal fans in series, creating a canalized airflow; an orifice plate (2) to measure the airflow rate; a heat booster (3) to heat the air, composed by 8 electric resistors, each one with a nominal potency of 400 W; a connection (4) between the air duct and the drying box; a drying box (5) in form of the rectangular prism with internal sizes of 0,32 m of height, 0,07 m of width, and 0,12 m of length with several removable compartments separated by grid; a system of air temperature measurement, composed by five temperature sensors, connected by digital multimeters.

The average air velocity in the drying process was calculated knowing the pressure drop on the orifice plate installed in the air duct. The measurement of the pressure drop was realized by oblique U-tube manometer with an alcohol. During the experiments, the air velocity was maintained constant. The grain samples, naturally moistened, were practically without impurity (dirty). The determination of the grain humidity substance was made through the measurements of humidity substance by device called DOLE 500, (made by De Leo), and by the measurements of the grain mass before and after the drying process, in each pre-established interval of time, using the analytical balance with precision of 0,01g. The result of these measurements in function of the time, represents the dynamic drying curves.

The air temperature was measured by five diode sensors. One of them was put in the beginning of the drying box and the others in its center. The readings were taken by the multimeters. To measure the grain temperature, a thermocouple sensor has been carefully introduced into the grain, which was duly put at the center of the corresponding compartment. The measurement process was analogous to the air temperature measurement.

The experiments were accomplished under ambient temperature and pressure conditions; air velocity and initial air temperature (drying temperature) were maintained constant for each experiment.

10. Results

The realized calculation shown that the difference between the results obtained by the methods of MacCormack and of Crank-Nicholson is negligible. For example, Fig. (3) presents a part of the drying curves calculated by these methods, inside a chosen interval with the biggest difference between the compared methods.

Even with the fulfillment on each temporal step of the progressive and inverse substitution in L-U decomposition method, the Crank-Nicholson method was much more profitable, because was allowed to increase the CFL numbers, (it means augment of step in the time that is the march variable) and consequently to decrease substantially the time of the calculation.

At the same time, the value of CFL number for the Crank-Nicholson method, in the analyzed interval, could not exceed 3 (in spite of absolute stability of the method), because of numerical instability.

Varying the parameters involved in the model, the numerical simulations were made. Figures (4)-(7) show some of this simulations, comparing with the experimental results. Figure (4) shows the comparison between the experimental data of Soares (1986) and the authors' simulations for the initial section of the thick layer that may be considered as the thin layer. The satisfactory coincidence for all the initial drying temperatures, shows that the developed model describes well the transference of the water mass between the grains and the air. The heat transfer phenomena doesn't affect this process because the grains and the air have the same initial temperature. The model takes into account the internal resistance to water transport in the grain, utilizing an experimental data of drying in thin layer for calculation of the mass flux Φ_m.

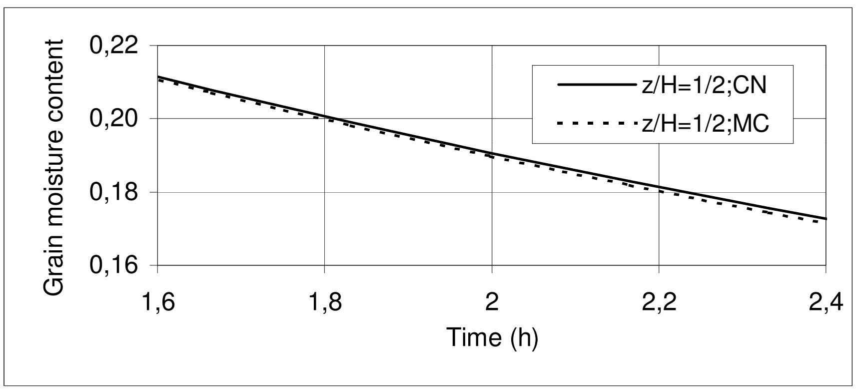

Figure 3. Comparison of the numerical applied methods: ———, Crank-Nicholson; - - - -, MacCormack.

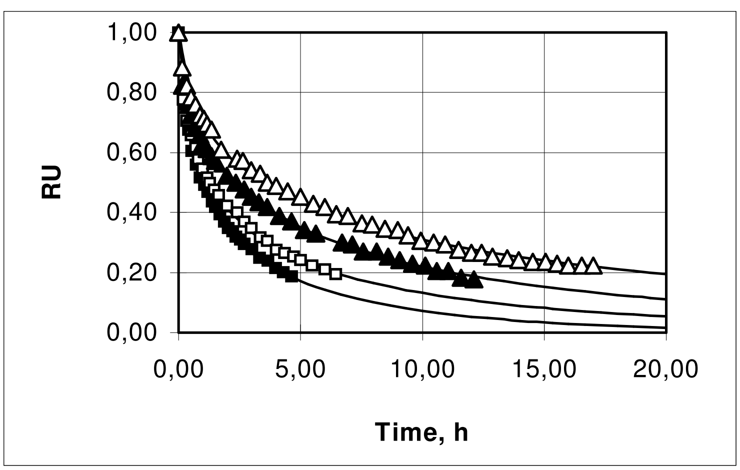

Figure 4. Comparison between the experimental data of Soares (1986) and the authors' simulation: ■ 70^0C; □ , 60^0C; ▲, 45^0C; Δ, 30^0C; —— , predicted.

A comparison of the experimental and simulated grain drying dynamics for Tg_0 = 25ºC, Ta_0 = 65ºC, presented in Fig. (5), shows a reasonable coincidence.

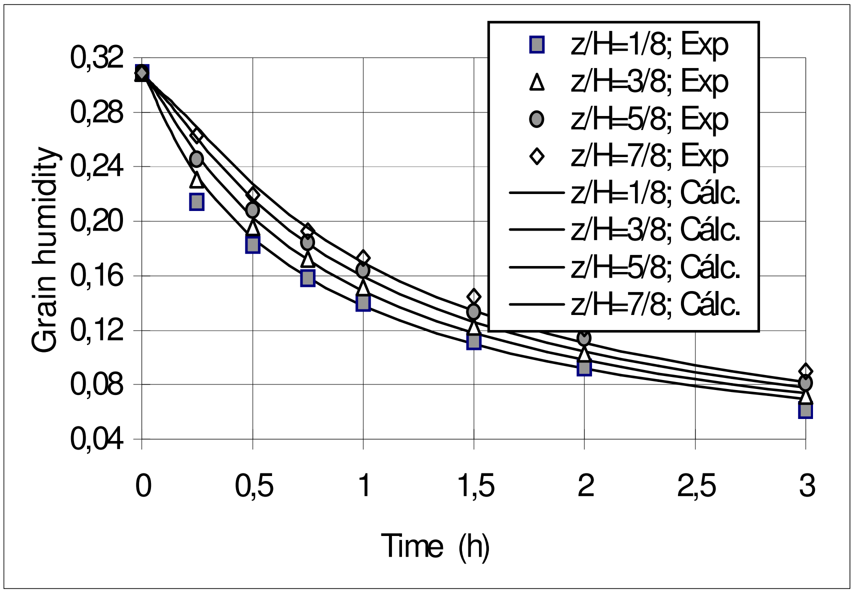

Figure 5. Dynamics of soy grain drying. Comparison between the experimental and the simulated data. Ta = 65ºC; X_0=0,31b.u.;Va=4,75m/s.

Comparing the experimental and simulated data of grain heating in Fig. (6), shows a good coincidence at the end of the drying process, and enough difference in initial moments. It indicates that the model has to be improved in order to obtain more suitable relationships for the heat transfer coefficient.

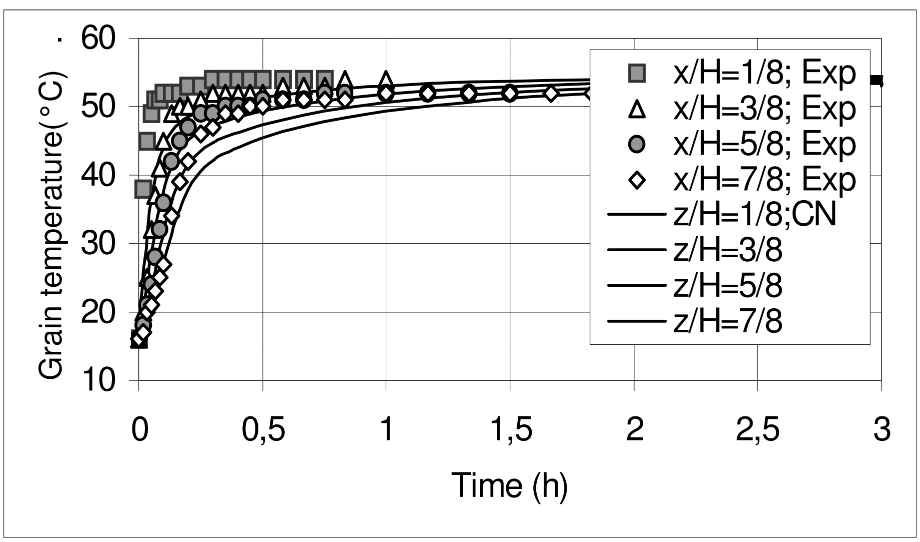

Figure 6. Grain temperature. Comparison between the experimental and the simulated data

Because of same motive the measured and simulated air temperatures in different sections of the working chamber, shown in Fig. (7), are noticeably distinguished in the initial moments of the drying process. It is possible that one part of the difference is caused by mistakes in the measurement of the air temperature, caused by the contact of the thermocouples with the grains surface.

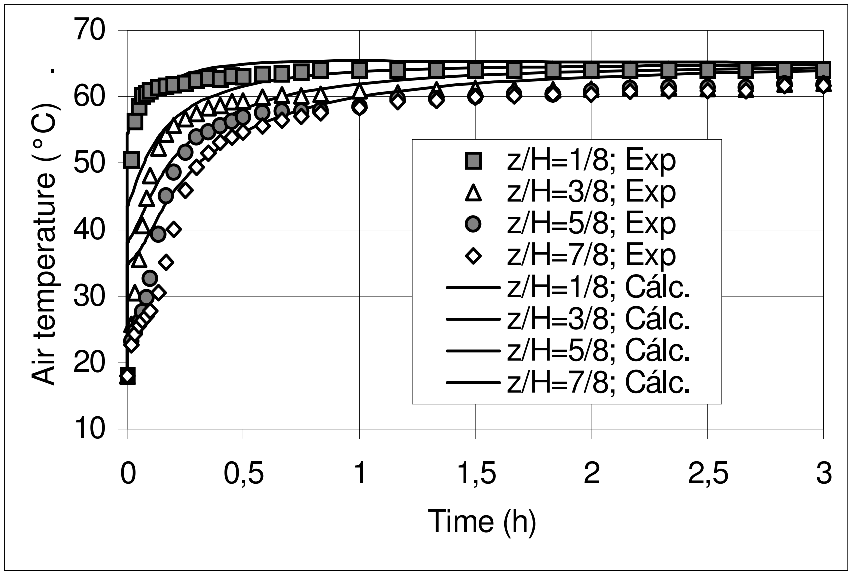

Figure 7. Air temperature variation. Comparison between the experimental and the simulated data.

Figure (8) presents a simulation of dynamics of air humidity variation in several sections of drying chamber. At the first moments of drying process the air humidity is increased and then begins smoothly to decrease.

11. Conclusion

The mathematical model and software for the parameters and functioning simulations of a fixed bed dryer were developed.

The equipment was developed and the dynamics drying curves, the grain and the air temperatures variation in a drying chamber were obtained.

The comparison made has shown that the developed model satisfactorily describes the process of mass transfer in the thick layer. But it is necessary to improve the model in the part of the heat transference between the grains and the air.

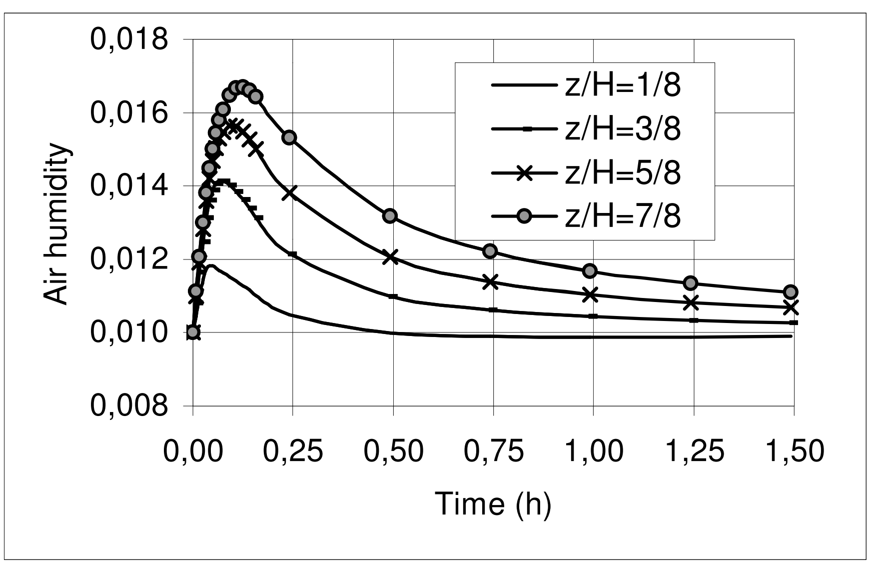

Figure 8. Dynamics of air humidity variation (simulated data).

12. Acknowledgement

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