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SIMULATION OF CONTINUOUS FLOW GRAIN DRYERS

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Abstract — Mathematical model and a computer program were developed to simulate the performance of continuous flow grain dryers. The mass and heat transfer processes were described by a system of four non-linear partial differential equations. This system was solved by the MacCormack method. Methods of Neumann and Matrix (considering the border conditions) were used for analysis of the convergence. The source-terms in these equations were defined by auxiliary semi-empirical equations, which were obtained by experimental data in the thin layer. In order to validate the model, the experiments were conducted in fixed bed. Simulations were made for various schemes of continuous flow dryers, including energy saving scheme with recycling the air for cooling and for drying of grain. To determine the initial conditions at the entrance to each section of dryer the iterative process was used. The computer simulations permitted to evaluate energy efficiency of each scheme, the duration of the drying process for geometry and initial moisture content of grains chosen.

Keywords — Grain drying, Mathematical model, Heat and mass transfer coefficients, Energy saving scheme, Application in Agriculture.

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, França *et. al*., 1994). 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 (Luikov, 1966, Laws and Parry, 1983, 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 (Jayas *et. al*. 1991, Parti, 1993). Thus, the goodness of thin-layer drying models essentially defines the simulation results for bulk drying.

This paper is dedicated to modeling of continuous flow grain dryers, which widely used for drying of soybeans in the Rio Grande do Sul State (Figure 1).

Space dimension and boundary conditions of problem depends on the chosen drying scheme. The use of exhaust air increases system effectiveness but at the same time leads to an increase in air humidity for drying. To properly evaluate the effectiveness of these conditions is very important to know a wide range of influence of the initial air humidity on the dynamics of drying.

The principal objectives of the present work are:

a) to create a mathematical model of drying of grains;

b) to develop a software for simulation of the continuous flow dryer with multiple stages;

c) to carry out simulations to evaluate the efficiency of some schemes dryers.

2 Method

2.1 Mathematical model

Figure 1 presents one of the investigated schemes of continuous flow grain dryers with 3 drying stages and cooling chamber. Ambient air passes through the cooling chamber, heats, then mixed with the heated furnace air and this mixture A enters in 3rd stage. Air leaving the third stage, mixes up with the heated furnace air and the obtained mixture B enters in 2nd stage. Similarly, the mixture C enters in 1st stage, heats up and dries the grain entering from above in 1st stage and then used air is thrown out in atmosphere.

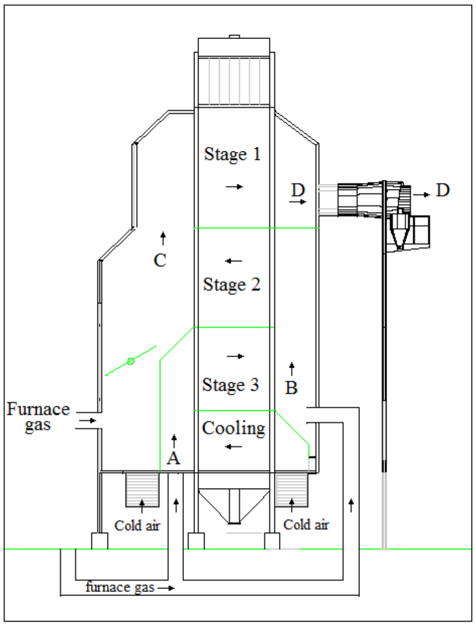

Figure 1. Layout of continuous flow grain dryer.

In summary, crossflow drying model for these conditions is:

$$\begin{cases} \dfrac{\partial X}{\partial t}+V_x\dfrac{\partial X}{\partial x}+V_y\dfrac{\partial X}{\partial y}=-\dfrac{\Phi_m a}{\rho_g} \\ \dfrac{\partial T_g}{\partial t}+V_x\dfrac{\partial T_g}{\partial x}+V_y\dfrac{\partial T_g}{\partial y}=-\dfrac{a\{\Phi_h+\Phi_m[H_v+(C_{pv}-C_{pw})T_g]\}}{\rho_g(C_{pg}+XC_{pw})} \\ \dfrac{\partial Y}{\partial t}+V_x\dfrac{\partial Y}{\partial x}+V_y\dfrac{\partial Y}{\partial y}=\dfrac{\Phi_m a(1-\varepsilon)}{\rho_a\varepsilon} \\ \dfrac{\partial T_a}{\partial t}+V_x\dfrac{\partial T_a}{\partial x}+V_y\dfrac{\partial T_a}{\partial y}=\dfrac{a(1-\varepsilon)}{\rho_a\,\varepsilon}\cdot\dfrac{\Phi_m C_{pv}(T_g-T_a)+\Phi_h}{C_{pa}+C_{pv}Y} \end{cases} \qquad (1)$$

where X is the moisture content; Y is the air humidity; a is grain surface area/volume ratio (m^{-1}); H_v is latent heat of the water vaporization ($J\cdot kg^{-1}$); C_{pg} is the specific heat of the grain ($J\cdot kg^{-1}\cdot°C^{-1}$); C_{pv} is the specific heat of the water's vapor ($J\cdot kg^{-1}\cdot°C^{-1}$); C_{pw} is the specific heat of the water ($J\cdot kg^{-1}\cdot°C^{-1}$); ρ_g is the specific mass of the grain ($kg\cdot m^{-3}$); ρ_a is specific mass of the air ($kg\cdot m^{-3}$); ε is porosity; V_x is the air velocity ($m\cdot s^{-1}$); V_y is the grain velocity ($m\cdot s^{-1}$); T_a is the air temperature (°C); T_g is the grain temperature (°C); Φ_h is the heat flux ($kg\cdot m^{-2}\cdot s^{-1}$); Φ_m is the mass flux ($kg\cdot m^{-2}\cdot s^{-1}$).

The heat flux, Φ_h, was calculated in according with dependences, presented by Khatchatourian and Oliveira (2006). 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 to calculate Φ_m. The mathematical model is presented by system of two ordinary differential equations (Khatchatourian, 2012):

$$\begin{cases} \dfrac{dX_1}{dt}=-k_1(X_1-X_2); \\ \dfrac{dX_2}{dt}=-k_1(X_2-X_1)-q\cdot k_2(X_{g0}-X_e)^{n-1}X_2^n \end{cases} \qquad (2)$$

where X_1 and X_2 are average relative grain humidities in 1th and 2nd grain 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.

Second equation in system (2) 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_x=0.9 m/s (q=1). 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.

The initial and boundary conditions for each stage depend on the parameters in the output of the previous stage located immediately above. Furthermore the inlet air humidity depends on the amount of air recirculation. In other words, these conditions depend on the number of stages and the scheme of distribution and recirculation of air.

Two of the various schemes studied in this work are shown in Figure 2.

For scheme 1 (Figure 2) the initial and boundary conditions for stage i are described as follows:

The boundary conditions:

Xg_1(t, x, 0)=Xg0 (0.19 b.u.); Tg_1(t, x, 0)=Tg0 (20°C); T_1(t, 0, y)=Ta_1 (120°C); T_2(t, 0, y)=Ta_2 (100°C); T_3(t, 0, y)=Ta_3 (80°C).

The boundary conditions for variables Xg_2(t, x, H_1), Tg_2(t, x, H_1), Xg_3(t, x, H_1+H_2), Tg_3(t, x, H_1+H_2), Xg_c(t, x, $H_1+H_2+H_3$), Tg_c(t, x, $H_1+H_2+H_3$), Ya_1, Ya_2, Ya_c are determined during the calculations by an iterative process.

For scheme 1 the values of the parameters were taken following: H_1=4.16 m; H_2=3.4 m; H_3=2.9 m; L=0.167 m; air velocity V_x=0.164 m/s.

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The initial conditions:

$Xg_i(0, x, y)=Xg0$; $Tg_i(0, x, y)=Tg0$; $Ya_i(0, x, y)=Ya0$; $Ta_i(0, x, y)=Tg0$ (i=1, 2, 3, c).

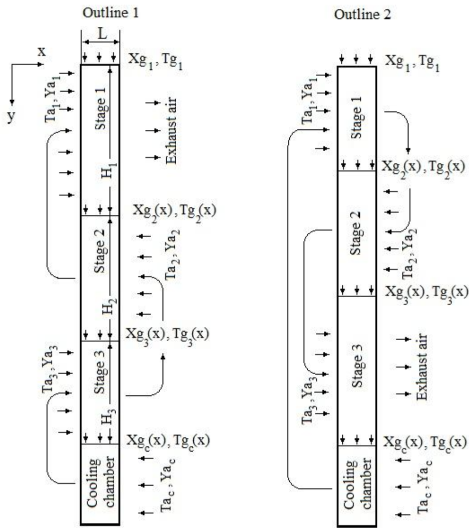

Figure 2. Investigated dryer outlines

2.2 Solution of the partial differential equations

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

$$\frac{\partial U}{\partial t}+V_x\frac{\partial U}{\partial x}+V_y\frac{\partial U}{\partial y}=F(t,x,y,U) \qquad (3)$$

where $U=(Xg\;Tg\;Ya\;Ta)^T$.

To solve the system used a 2-D MacCormack's method with scheme "time-split" (MacCormack, 1971).

The iterative MacCormack's method with the "time-split" transforms the two-dimensional problem in one-dimensional problems. Considering the differential operator L_x, related to the spatial variable x:

$$U^*_{i,j}=L_x(\Delta t_x)U^n_{i,j} \qquad (4)$$

the MacCormack's method (1969, 1971) corresponds to the sequence of operations:

Predictor:

$$\overline{U^*_{i,j}}=U^n_{i,j}-\frac{\Delta t_x\cdot V_x}{\Delta x}\left[U^n_{i+1,j}-U^n_{i,j}\right]+\Delta t_x F^n_{i,j} \qquad (5)$$

Corrector:

$$U^*_{i,j}=\frac{1}{2}\left[U^n_{i,j}+\overline{U^*_{i,j}}-\frac{\Delta t_x\cdot V_x}{\Delta x}\left(\overline{U^*_{i,j}}-\overline{U^*_{i-1,j}}\right)\right]+\frac{\Delta t_x\overline{F^*_{i,j}}}{2} \qquad (6)$$

The asterisk (*) was used to denote the parameters with intermediate time steps.

L_y operator is defined similarly substituting V_x and t_x by V_y and t_y. The MacCormack's method with the "time-split" can be presented as:

$$U^{n+1}_{i,j}=L_x\left(\frac{\Delta t_x}{2}\right)L_y\left(\Delta t_y\right)L_x\left(\frac{\Delta t_x}{2}\right)U^n_{i,j} \qquad (7)$$

Assuming V_x and V_y as constants, the operator L_x for half the time step and the derivatives with respect to x, is composed of:

Predictor:

$$\overline{U^{*n+1/2}_{i,j}}=U^n_{i,j}-\frac{\Delta t_x Vx}{2\Delta x}\left[U^n_{i+1,j}-U^n_{i,j}\right]+\frac{\Delta t_x}{2}F^n_{i,j} \qquad (8)$$

Corrector:

$$U^{*n+1/2}_{i,j}=\frac{1}{2}\left[U^n_{i,j}+\overline{U^{*n+1/2}_{i,j}}-\frac{\Delta t_x V_x}{2\Delta x}\left(\overline{U^{*n+1/2}_{i,j}}-\overline{U^{*n+1/2}_{i-1,j}}\right)\right]+\frac{\Delta t_x\overline{F^{*n+1/2}_{i,j}}}{2} \qquad (9)$$

The operator L_y for full time step and the derivatives with respect to y, is formed:

Predictor:

$$\overline{U^{**}_{i,j}}=U^{*n+1/2}_{i,j}-\frac{\Delta t_y V_y}{\Delta y}\left[U^{*n+1/2}_{i,j+1}-U^{*n+1/2}_{i,j}\right]+\Delta t_y F^{*n+1/2}_{i,j} \qquad (10)$$

Corrector:

$$U^{**}_{i,j}=\frac{1}{2}\left[U^{*n+1/2}_{i,j}+\overline{U^{**}_{i,j}}-\frac{\Delta t_y V_y}{\Delta y}\left(\overline{U^{**}_{i,j}}-\overline{U^{**}_{i,j-1}}\right)\right]+\Delta t_y\overline{F^{**}_{i,j}} \qquad (11)$$

And again the operator L_x:

Predictor:

$$\overline{U^{n+1/2}_{i,j}}=U^{**}_{i,j}-\frac{\Delta t_x V_x}{2\Delta x}\left[U^{**}_{i+1,j}-U^{**}_{i,j}\right]+\frac{\Delta t_x}{2}F^{**}_{i,j} \qquad (12)$$

Corrector:

$$U^{n+1}_{i,j}=\frac{1}{2}\left[U^{**}_{i,j}+\overline{U^{n+1/2}_{i,j}}-\frac{\Delta t_x V_x}{2\Delta x}\left(\overline{U^{n+1/2}_{i,j}}-\overline{U^{n+1/2}_{i-1,j}}\right)\right]+\frac{\Delta t_x\overline{F^{n+1/2}_{i,j}}}{2} \qquad (13)$$

Two iterative processes were used for simulation: the first (internal) was used to determine the boundary conditions between stages and air humidity in the side entrance to each stage (which depends on the composition of the air furnace + fresh air + air recirculation). The second iterative process (external) was applied to calculate the drying time to achieve the required average moisture content of grain in the dryer outlet (13% w.b.), i.e., to calculate the grain velocity, V_y.

3 Results

Simulation results are shown in Figures 3-5.

It can be seen (Figure 3), the drying process in the initial (x / L = 1) and final (x / L = 0) sections occurs the most rapidly. In the middle section (x / L = 0.5) drying curve lags behind the average.

Air and grain temperatures in the different cross-sections (Figure 4) differ significantly in only 1st stage. For subsequent stages the temperature difference decreases.

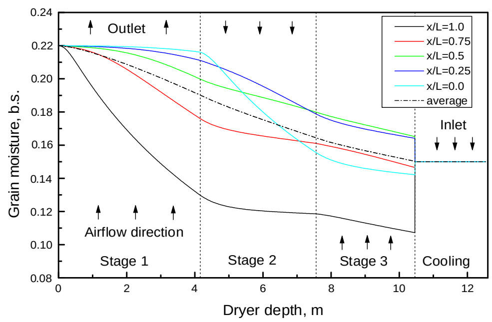

Figure 3. Distribution of moisture content of grain in the dryer 1 at a steady state

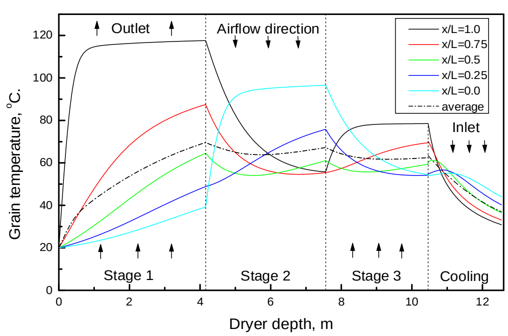

Figure 4. Distribution of grain temperature in the dryer 1 at a steady state

The simulations showed (Figure 5) that the reversing of flow direction equalizes the distribution of parameters in the transverse dryer direction and accelerates the drying process a little. The recirculation of air in the system increases the humidity of the drying air and for cases considered slightly increases the drying time. Simultaneously, reutilization of heat, obtained from grain mass in the earlier drying stages, in this case saves up to 40% of fuel (this value depends on the chosen scheme of the dryer).

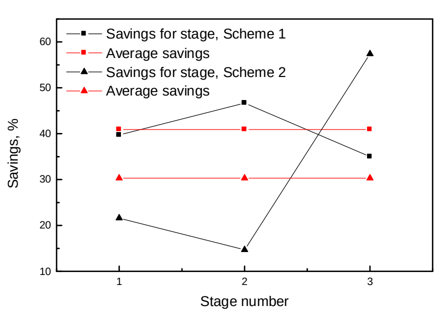

Figure 5. Comparison of fuel saving because of the air recirculation for Outlines 1 and 2.

4 Conclusion

The mathematical model, algorithm and computer program for simulation of the continuous flow dryer with the system of recycling of hot air were developed.

The iterative MacCormack's method with scheme "time-split" which transformed the two-dimensional problem in one-dimensional problems was successfully applied for solution of system of non-linear partial differential equations.

The dryer's efficiency significantly depends from reuse of the heated air.

Average fuel savings for the cases considered were between 30-40% depending on the chosen scheme.

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