DRYING OF GRAINS IN CONVEYOR DRYER AND CROSS FLOW: A NUMERICAL SOLUTION USING FINITE-VOLUME METHOD

Raimundo Pereira de Farias¹, Deivton Costa Santiago², Pedro Ronaldo Herculano de Holanda³, Antonio Gilson Barbosa de Lima⁴

ABSTRACT

The drying of solids in cross flow band conveyor dryer (continuous operation system) in which particles (thin-layer) move in a wire net conveyor was theoretically studied. A mathematical modeling that considers the influence of the bed porosity and the transient terms in the drying process was developed. The finite volume method and upwind formulation to convective terms were used to solve numerically the governing conservation equations. The results of the relative humidity and temperature of the air and temperature and moisture content of the material (yellow corn kernel) along the drying process are presented and analyzed to examine the influence of the main drying parameters on the quality of the product in the end of the process. This study can be used to help researchers in the optimization of this and others types of driers under small modifications.

Keywords: drying, finite-volumes, dryer, net conveyor, corn

SECAGEM DE GRÃOS EM SECADOR DE ESTEIRA E FLUXOS CRUZADOS: UMA SOLUÇÃO NUMÉRICA USANDO O MÉTODO DOS VOLUMES FINITOS

RESUMO

Este trabalho tem como objetivo, estudar a secagem de sólidos em secador de esteira e fluxos cruzados (sistema de operação contínua) em que partículas (em camada fina) movem-se em uma esteira transportadora. O modelo proposto considera a influência da porosidade do leito e os termos transitórios no processo de secagem. As equações que descrevem o problema físico foram resolvidas numericamente utilizando o método numérico dos volumes finitos considerando o esquema upwind como função de interpolação para os termos convectivos. Para verificar a influência dos principais parâmetros de secagem na qualidade do produto no final do processo, resultados da temperatura e umidade relativa do ar de secagem, e do teor de umidade e temperatura do grão de milho durante o processo de secagem são mostrados e analisados. Esta pesquisa pode ser usada para ajudar pesquisadores na otimização deste e de outros tipos de secadores realizando poucas modificações no modelo.

Palavras-chave: secagem, volumes finitos, secador, esteira transportadora, milho
INTRODUCTION

Grains are normally harvested still fairly moist, therefore, they must be dried to minimize the water content and to reduce spoilage problems due to the action of the microorganisms (Giner et al., 1998; Rumsey & Rovedo, 2001). These agricultural products are dried through two techniques: fixed bed and continuous flow bed (concurrent, counter and cross-flow beds).

One of the most common continuous drying flows for grains is the cross-flow dryer. Nowadays, it is necessary to study these driers with more details because of the high cost of the dryer, in particular cross flow one, and they produce considerable stress and cracking on the grain kernel. In general way, the drying residence time of grain in the drier has been obtained as a function of the following variables: the grain bed thickness layer inside the dryer along airflow direction, initial and final moisture content, initial temperature, the grains thermo-physical properties, air flow rate, inlet temperature, and the air humidity ratio.

A large number of researchers has reported cross-flow dryer modeling. The models consider the void fraction and/or the transient air-drying condition within the bed neglected (Bakker-Arken et al., 1974; Sokhansanj & Wood, 1991; Brokker et al., 1992; Fasina & Sokhansanj, 1993; Barrozo et al., 1996; Motta-Lima et al., 1996; Li et al., 1997; Liu & Bakker-Arkema, 2001a-b). Other researchers present numerical studies considering void fraction and/or the transient terms in the mathematical model (Eltigani & Bakker-Arkena, 1987; Vasconcelos & Alsina, 1992; França et al., 1994; Soponronnairit et al., 1996; Giner et al., 1996; Giner et al., 1998). Experimental study has been reported in the literature too (Sartori, 1992; Pimentel & Sartori, 1998; Giner & Bruce, 1998; Yang et al., 2000; Siebenmorgem et al., 2000).

It is necessary to know the effect of the drying parameters in the moisture removal and temperature of the solid during the drying process in order to obtain the better drying conditions and to save energy. The aim of this work is to present a numerical model, using the finite volume method, to predict the changes of the air temperature and relative humidity, and the solid temperature and moisture content during drying process in a continuous cross flow belt dryer considering existence of void fraction and all transient terms in the conservation equations.

MATHEMATICAL MODEL

The development of the conservation equation is based on the control volume illustrated in Figure 1. The following assumptions as a simplification of the model to describe the drying process of solids in a conveyor band dryer have been made:

- a) The volume shrinkage is negligible during the drying process.
- b) The temperature and moisture content gradients within the individual particle are negligible along the process.
- c) Heat conduction among the particles is negligible.
- d) Heat loss of the dryer to the surrounding is negligible.
- e) Air and grain flows are plug-type.

According to the assumptions, the following partial differential equations are obtained to model the transient cross flow drying process in a belt conveyor dryer:

\[ \frac{\partial (\rho_s x)}{\partial t} + \frac{\partial}{\partial y} \left( \rho_s \frac{w}{\varepsilon} x \right) = -\frac{\rho_p}{\varepsilon} \frac{\partial \overline{M}}{\partial t} \]  \hspace{1cm} (1)

- Solid

\[ \frac{\partial \overline{M}}{\partial t} = \text{Thin layer drying equation} \] \hspace{1cm} (2)

\[ \frac{\partial (\rho_s T)}{\partial t} + \frac{\partial}{\partial y} \left( \rho_s \frac{w}{\varepsilon} T \right) = -A' h_e (T - \overline{h}) \] \hspace{1cm} (3)

where \( \rho_s \) is the air density, \( x \) is the humidity ratio, \( w_a \) is the air velocity, \( \varepsilon \) is the porosity, \( \rho_p \) is the product density, \( \overline{M} \) is the average moisture content, \( y \) is the Cartesian coordinate and \( t \) is the time.
where \( T \) is the air temperature, \( A^* \) is the surface area of the solid per volume unit of the bed, \( h_c \) is the convective heat transfer coefficient, \( \bar{\theta} \) is the average temperature of the solid, \( c_s \) and \( c_v \) are the specific heat of the air and vapor, respectively.

\[
\begin{align*}
\frac{\partial}{\partial t} (\rho_p \bar{\theta}) &= \frac{A^* h_c (T - \bar{\theta})}{c_p + c_w M} + \\
&\quad + \frac{[h_{fg} + c_v (T - \bar{\theta})]}{c_p + c_w M} \rho_p \frac{\partial M}{\partial t} \\
\end{align*}
\]  

(4)

where \( h_{fg} \) is the heat of vaporization of the product and \( c_w \) is the specific heat of water.

The following initial and boundary conditions were used:

\[
\begin{align*}
\overline{M}(y, t = 0) &= M_0 \\
\bar{\theta}(y, t = 0) &= \theta_e \\
T (y=0, t) &= T_{oi} \\
x (y=0, t) &= x_o
\end{align*}
\]

(5a-d)

---

**Figure 1** – Schematic representation of the continuous cross flow belt conveyor dryer

Corn grain is usually harvested at high moisture content for safe storage. So, it is necessary to dry this agricultural product to storage and to prevent quality deterioration. As application, the methodology was used to describe the drying of yellow corn grains. In this sense, Brokker et al. (1992) report the following thin-layer drying equation to describe drying rate:

\[
\frac{\partial \overline{M}}{\partial t} = \frac{M_e - \overline{M}}{3600 \left( A^2 + \frac{B t}{900} \right)^{1/2}}
\]

(6)

where \( t \) is in seconds, \( M_e \) is the equilibrium moisture content, \( A = -1.7054824 + 0.0087917 \bar{\theta} \) and \( B = 148.60862 e^{-0.059418 \bar{\theta}} \).

The heat of vaporization, equilibrium moisture content, specific surface area, dry solid density and specific heat of the corn grain,
and the void fraction of the bed are given by (Brokker et al., 1992).

\[ h_{fg} = (2502.2 - 2.39T) \left[ 1 + 1.2925e^{-16.981M} \right] \text{kJ/kg} \]

\[ M_e = \frac{L}{100} \left[ \frac{\ln(1 - x)}{8.6541x10^{-7}(T + 49.81)} \right]^{1/1.8634} \]  

\[ c_p = \left[ 1.361 + 3.97 \frac{M}{(1 + M)} \right] \text{kJ/kgK} \]

\[ \rho_p = 650 \text{kg/m}^3 \]

\[ \varepsilon = 0.44 \]

\[ A^* = 784 \text{ m}^2 / \text{m}^3 \]

The specific heat (Jumah et al., 1996), density, relative humidity, absolute temperature, Universal constant applied to the air, saturation pressure of vapor and local atmospheric pressure are given by (Rossi, 1987):

\[ c_v = 1.8830 - 0.16737x10^{-3}T_{abs} + 0.84386x10^{-6}T_{abs}^2 - 0.26966x10^{-9}T_{abs}^3 \text{kJ/kgK} \]  

\[ c_w = 2.82232 + 1.18277x10^{-2}T_{abs} - 3.5047x10^{-5}T_{abs}^2 + 3.6010x10^{-8}T_{abs}^3 \text{kJ/kgK} \]

The heat transfer coefficient was obtained using the following equations (Brokker et al., 1992):

\[ h = \begin{cases} 101.4(\rho_ww_a)^{0.59} & \text{to } \rho_ww_a \geq 0.68 \text{ W/m}^2\text{C} \quad (10) \\ 99.6(\rho_ww_a)^{0.49} & \text{to } \rho_ww_a < 0.68 \end{cases} \]

\[ \text{UR} = \frac{P_{atm}^x a}{(8_a + 0.622)P_{vs}} \]

\[ P_v = 22105649.25 \exp\left[ -27405.53 + 97.5413T_{abs} - 0.146244T_{abs}^2 + 0.12558x10^{-3}T_{abs}^3 - 0.48502x10^{-7}T_{abs}^4 \right] / \left[ 4.34903T_{abs} - 0.39381.10^{-2}T_{abs} \right] \text{ Pa} \]

The specific heat of water on the vapor and liquid phases are given by (Jumah et al., 1996):

\[ c_v = 1.8830 - 0.16737x10^{-3}T_{abs} + 0.84386x10^{-6}T_{abs}^2 - 0.26966x10^{-9}T_{abs}^3 \text{kJ/kgK} \]  

\[ c_w = 2.82232 + 1.18277x10^{-2}T_{abs} - 3.5047x10^{-5}T_{abs}^2 + 3.6010x10^{-8}T_{abs}^3 \text{kJ/kgK} \]

\[ \text{The numerical solution} \]

Many numerical techniques can be used to solve the set of partial differential equations, for example, finite-element, finite-difference, Boundary-element and finite-volume methods (Patankar, 1980; Maliska, 1995; Versteeg and Malalasekera, 1995). In this work, the finite-volume method was used to discretize the basic equations integrating one under the control volume and time as illustrated in Figure 2.

![Figure 2 - Control volume used in this work](image-url)
The result of the integration is a set of linear equations in the discretized form as follows:

- **Grain:**
  
  \[ A_p \bar{\theta}_p = A_p^o \bar{\theta}_p^o + S_C^T \]  
  \[ \text{(10a)} \]

where

\[ A_p = \frac{\Delta z}{\Delta t_m} + \frac{\Delta z}{3600(A^2 + Bt/900)^{1/2}} \]

\[ A_p^o = \frac{\Delta z}{\Delta t_m} \]

\[ S_C^T = \frac{\Delta y}{\Delta t} \]

- **Mass:**
  
  \[ A_p x_p = A_S x_S + A_p^o x_p^o + S_C^x \]
  \[ \text{(10d)} \]

where

\[ A_p = \rho_p \frac{\Delta y}{\Delta t} + \rho_a \frac{w_a}{\varepsilon} \]

\[ A_S = \frac{w_a}{\varepsilon} \]

\[ A_p^o = \rho_p \frac{\Delta y}{\Delta t} \]

\[ S_C^x = -\frac{\rho_p \Delta M}{\varepsilon} \frac{\partial}{\partial t} dy \]

A computational code, using the software Mathematica\textsuperscript{6}, was implemented to obtain the numerical results. The time step was evaluated by \( \Delta t = \Delta y / w_a \) in the equations applied to the air. To the grains, \( \Delta z = u_p (\text{npy} - 1) \Delta t \) and \( \Delta t_m = (\text{npy} - 1) \Delta t \), where npy is the nodal point number in the direction y. During this \( \Delta t_m \), the grains within the volume \( \Delta z H \) were assumed stationary and thus \( T, x, M \) and \( \bar{\theta} \) were obtained to the fixed bed drying. Upwind scheme as interpolation function to convective terms along the z-direction was used in all equations. More details about this procedure can be found in Santiago et al., (2002) and Farias (2003).

**Condensation of water**

After calculating \( \bar{M}, \bar{\theta}, T \) and \( x \) in each position inside bed and drying time, the relative humidity is obtained. If this value is greater than 1 saturation or super saturation is assumed and condensation is modeled. The condensation of water may occur when a large amount of vapor of water is transported by the air and so cooled when it passes through cool grains.

The following procedure was used to model the condensation:

a) \( \bar{M}, \bar{\theta}, T \) and \( x \) are calculated in a y location inside the bed, and then \( P_{vs} \) and UR are obtained.
b) If UR>1, a new value of the absolute humidity $x=x_0+Ax$ is assumed $So$, go to passes c. If UR ≤ 1 stop the condensation and go to new y location.

c) Using the new value $x$, we calculate the new values of $\bar{M}$, $\bar{\theta}$ and $T$.

d) Using the new value of $T$, we calculate $P_{vs}$ and $UR$ and return to passes b.

The new value of $\bar{M}$ is given by:

$$\bar{M} = \bar{M}_{bc} + \frac{\rho_d W_a \Delta x}{\rho_p u_p \theta_y} (x_{bc} - x) \quad (11)$$

The new value of $T$ is given by:

$$T = -\frac{\rho_d W_a}{u_p} \frac{\Delta x}{dz} \left( \frac{(c_a + c_v x)}{u_p} \right) + \frac{\rho_d W_a \Delta x}{u_p} \left( c_a + c_v x \right) \quad (12)$$

In this procedure, $\Delta x = 10^{-8}$ kg/kg was used. The subscript “bc” refers to values before condensation.

RESULTS AND DISCUSSIONS

In order to analyze the effects of the air drying conditions on the moisture removal of the yellow corn grain, several conditions are chosen for simulation. Table 1 presents all drying condition used in the work as well as the final moisture content, total drying time and length of the dryer.

Numerical results of the average moisture content of yellow corn grain are compared with experimental data to fixed bed drying reported in the literature to validate the methodology (Fortes et al., 1978). The comparison is possible because $u_p<<w_a$ ($u_p = 0.005$m/s). Figure 3 illustrates this comparison during drying process in y=0.0 m to test 1. It is verified that a very few errors were obtained.

Figures 4 and 5 show the effect of air-drying inlet conditions on the moisture removal and temperature of the grain. It is verified that the drying temperature has strong effect on the grain temperature stronger than on the moisture content. However, the increase of the grain temperature increases the drying rate and the grain reaches the temperature of the air and its equilibrium moisture content more quickly. This situation may cause damage to the grain quality.
Table 1 - Air and grain conditions used in this work, final moisture content, total drying time and length at the dryer

<table>
<thead>
<tr>
<th>Test</th>
<th>Grain M₀ (kg/kg)</th>
<th>Grain H (m)</th>
<th>Grain θ₀ (°C)</th>
<th>Air Mₐ (kg/kg)</th>
<th>Air x₀ (kg/kg)</th>
<th>Air wₐ (m/s)</th>
<th>Air T₀ (°C)</th>
<th>Air RH (%)</th>
<th>t (s)</th>
<th>L (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.30</td>
<td>0.1</td>
<td>0.180</td>
<td>0.011340700</td>
<td>1.63</td>
<td>75</td>
<td>4.7</td>
<td>8000.00</td>
<td>4907.90</td>
<td>24.54</td>
</tr>
<tr>
<td>2</td>
<td>0.30</td>
<td>0.2</td>
<td>0.231</td>
<td>0.002628163</td>
<td>1.50</td>
<td>30</td>
<td>10.0</td>
<td>8000.00</td>
<td>40.00</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.30</td>
<td>0.2</td>
<td>0.215</td>
<td>0.004583815</td>
<td>1.50</td>
<td>40</td>
<td>10.0</td>
<td>8000.00</td>
<td>40.00</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.30</td>
<td>0.2</td>
<td>0.177</td>
<td>0.012514130</td>
<td>1.50</td>
<td>60</td>
<td>10.0</td>
<td>8000.00</td>
<td>40.00</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.30</td>
<td>0.2</td>
<td>0.158</td>
<td>0.019776720</td>
<td>1.50</td>
<td>70</td>
<td>10.0</td>
<td>8000.00</td>
<td>40.00</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.30</td>
<td>0.2</td>
<td>0.194</td>
<td>0.000761409</td>
<td>1.50</td>
<td>50</td>
<td>1.00</td>
<td>8000.00</td>
<td>40.00</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.30</td>
<td>0.2</td>
<td>0.195</td>
<td>0.003825780</td>
<td>1.50</td>
<td>50</td>
<td>5.00</td>
<td>8000.00</td>
<td>40.00</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.30</td>
<td>0.2</td>
<td>0.196</td>
<td>0.007698940</td>
<td>1.50</td>
<td>50</td>
<td>10.0</td>
<td>8000.00</td>
<td>40.00</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.30</td>
<td>0.2</td>
<td>0.198</td>
<td>0.015590900</td>
<td>1.50</td>
<td>50</td>
<td>20.0</td>
<td>8000.00</td>
<td>40.00</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.30</td>
<td>0.2</td>
<td>0.200</td>
<td>0.031983900</td>
<td>1.50</td>
<td>50</td>
<td>40.0</td>
<td>8000.00</td>
<td>40.00</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>0.30</td>
<td>0.2</td>
<td>0.202</td>
<td>0.049242300</td>
<td>1.50</td>
<td>50</td>
<td>60.0</td>
<td>8000.00</td>
<td>40.00</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>0.30</td>
<td>0.2</td>
<td>0.134</td>
<td>0.002923429</td>
<td>1.50</td>
<td>80</td>
<td>1.00</td>
<td>8000.00</td>
<td>40.00</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>0.30</td>
<td>0.2</td>
<td>0.141</td>
<td>0.030526000</td>
<td>1.50</td>
<td>80</td>
<td>10.0</td>
<td>8000.00</td>
<td>40.00</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>0.30</td>
<td>0.2</td>
<td>0.146</td>
<td>0.064204200</td>
<td>1.50</td>
<td>80</td>
<td>20.0</td>
<td>8000.00</td>
<td>40.00</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>0.30</td>
<td>0.2</td>
<td>0.154</td>
<td>0.143195100</td>
<td>1.50</td>
<td>80</td>
<td>40.0</td>
<td>8000.00</td>
<td>40.00</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>0.30</td>
<td>0.2</td>
<td>0.163</td>
<td>0.242745300</td>
<td>1.50</td>
<td>80</td>
<td>60.0</td>
<td>8000.00</td>
<td>40.00</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>0.30</td>
<td>0.1</td>
<td>0.188</td>
<td>0.014897320</td>
<td>1.50</td>
<td>80</td>
<td>5.00</td>
<td>4000.00</td>
<td>4000.00</td>
<td>20.00</td>
</tr>
<tr>
<td>18</td>
<td>0.30</td>
<td>0.2</td>
<td>0.138</td>
<td>0.014897320</td>
<td>1.50</td>
<td>80</td>
<td>5.00</td>
<td>8000.00</td>
<td>40.00</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>0.30</td>
<td>0.3</td>
<td>0.138</td>
<td>0.014897320</td>
<td>1.50</td>
<td>80</td>
<td>5.00</td>
<td>8000.00</td>
<td>40.00</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>0.30</td>
<td>0.5</td>
<td>0.152</td>
<td>0.014897320</td>
<td>1.50</td>
<td>80</td>
<td>5.00</td>
<td>6666.67</td>
<td>33.33</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>0.30</td>
<td>1.0</td>
<td>0.138</td>
<td>0.014897320</td>
<td>1.50</td>
<td>80</td>
<td>5.00</td>
<td>8000.00</td>
<td>40.00</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>0.30</td>
<td>0.1</td>
<td>0.226</td>
<td>0.003825788</td>
<td>0.00</td>
<td>0.10</td>
<td>5.00</td>
<td>8000.00</td>
<td>40.00</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>0.30</td>
<td>0.3</td>
<td>0.195</td>
<td>0.003825788</td>
<td>0.00</td>
<td>0.10</td>
<td>5.00</td>
<td>8000.00</td>
<td>40.00</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>0.30</td>
<td>0.5</td>
<td>0.204</td>
<td>0.003825788</td>
<td>0.00</td>
<td>0.10</td>
<td>5.00</td>
<td>8000.00</td>
<td>40.00</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>0.30</td>
<td>1.0</td>
<td>0.195</td>
<td>0.003825788</td>
<td>0.00</td>
<td>0.10</td>
<td>5.00</td>
<td>8000.00</td>
<td>40.00</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>0.30</td>
<td>0.2</td>
<td>0.195</td>
<td>0.003825788</td>
<td>0.00</td>
<td>0.10</td>
<td>5.00</td>
<td>8000.00</td>
<td>40.00</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>0.30</td>
<td>0.2</td>
<td>0.195</td>
<td>0.003825788</td>
<td>0.00</td>
<td>0.10</td>
<td>5.00</td>
<td>8000.00</td>
<td>40.00</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>0.30</td>
<td>0.2</td>
<td>0.195</td>
<td>0.003825788</td>
<td>0.00</td>
<td>0.10</td>
<td>5.00</td>
<td>8000.00</td>
<td>40.00</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>0.30</td>
<td>0.2</td>
<td>0.195</td>
<td>0.003825788</td>
<td>0.00</td>
<td>0.10</td>
<td>5.00</td>
<td>8000.00</td>
<td>40.00</td>
<td></td>
</tr>
</tbody>
</table>

** In y=0.0m.
**Figure 4** - The effect of the air-drying temperature under the average moisture content of the grain during drying process

**Figure 5** - The effect of the air-drying temperature under the grain temperature during drying process

Figures 6 and 7 show the air and grain temperatures within the bed in nine drying times to the six air-drying conditions. It is verified that the highest gradients occurs quickly in the drying of the grain and closed to entrance of the air in the dryer.

The high thermal gradients along the bed are not recommended because it produces non uniform drying and big thermal stress in the grain and it can cause cracking, fissures and deformation in the solid and reduce its quality in the end of the process.
Figure 6 - Air temperature distribution within the bed to nine drying times. a) UR=1%, b) UR=10% and c) UR=60%
Figure 7 - Grain temperature distribution within the bed to nine drying times. a) UR=1%, b) UR=10% and c) UR=60%
It can be observed, in the Figure 6c, that air temperatures only arrive until a certain limit, due to the relative humidity inside the bed reaches its maximum value. The grain temperature (Figure 7c) presents small thermal gradients. The grain temperature reaches temperature next wet bulb temperature of air-drying quickly because of the high relative humidity. It’s stabilized soon after. It is noticed that the temperature of the corn is equal to the wet bulb temperature of the air-drying at the surface of the product. In little time and at the first layers of products, the grain temperature rises slightly, due to the heating of the air and later it stays constant for the other points. It happens because the air reaches relative humidity of 100% in these positions. For large times, 13 and 26 seconds, the behavior of the product temperature in the beginning of the layer is opposed, and a little decreases of the grain temperature occurs. This is due to the dry bulb temperature of the air happening decreases to its wet bulb temperature maintaining the energy conservation of the control volume.

Figures 8 and 9 illustrate the effect of the height of the product layer in the moisture content and temperature of the grain. In these figures, it is observed that the increase of the height of the layer provides a smaller drying rate of the product, because the air is reaching saturation along the layer. In the same situation, the product reaches the air temperature in few seconds after initialized the drying process as before. Then, this parameter doesn’t affect the grain temperature strongly. The same behavior is verified to relative humidity (Figure 10a-b).

Figures 11a-b illustrate the effect of the relative humidity in the moisture removal of the corn grain for two initial temperatures, 50 ºC and 80ºC. It is verified that the relative humidity changes more the moisture content of the grain than the temperature. The increase of the relative humidity reduces the drying rate as expected. Then, with the decrease of UR, the moisture content of the corn grain decreases more quickly along the process. It reduces the air temperature in the bed, in any time except for the first 200 seconds of process. In this case, the air temperature reaches the wet bulb temperature, producing high temperature gradient in the first layers of the bed.

Figure 8 - The effect of layer height in the moisture removal during drying process of corn grain in y=H
Figure 9 - The effect of layer height in the grain temperature during drying process of corn grain in $y=H$.

Figure 10 - The effect of relative humidity in the corn grain temperature during the drying process: a) $T=50^\circ C$ and b) $T=80^\circ C$. 

Revista Brasileira de Produtos Agroindustriais, Campina Grande, v.6, n.1, p.1-16, 2004
Figures 12 and 13 illustrate the effect of air velocity in the moisture removal and temperature of corn grain during the drying process, respectively. The increases of the airflow rate caused a decrease of the moisture gradients and an increase of the drying rate of solid and considerable effects were verified on the heating rate of the grain. Then, the drying process is controlled by internal and external diffusion. By increasing of the air velocity, the grain reaches the equilibrium temperature more quickly.

Recently, there has been a substantial development in reducing the energy consumption of driers because drying is a very energy consumption process. This development happened in two directions: improvement of the actual drying processes to make them consume less energy, and improvement of heat recovery systems Therefore, the air in the outlet of the dryer can circulate again and it can be used to dry solid and to save energy, to low thickness layer and small relative humidity.

Figure 11 - The effect of relative humidity in the moisture removal during drying process of corn grain. a) T=50ºC and b) T=80ºC
CONCLUSIONS

The following conclusions can be summarized:

- The finite-volume method can be used to simulate the drying process in cross flow dryer because of the good agreement obtained by comparison between numerical and experimental data.
- The air temperature has more effect on the drying rate of corn grain than the airflow rate.
- It is possible to conclude that the mass transfer is controlled by internal diffusion, and external condition has secondary importance because airflow rate doesn’t affect the drying rate.
- The grain reaches the inlet air temperature in few seconds of drying for all drying conditions.
- During drying process, low moisture content gradients within the bed were obtained. It is due to the small thickness layer of the grain that was used for the simulation.
Drying of grains in cross flow conveyor dryer: a numerical solution using finite-volume method

- The higher gradients of the air temperature inside of the bed happen in the first process instants (" 400,00s) for any air relative humidity;
- For high relative humidity (around 100%) condensation of water in the bed happens. In this location, the air temperature is equaled to the wet bulb temperature of the air, mainly in the few instants of drying;
- When the thickness layer of the product (corn grain) and the relative humidity of the air drying increase, the drying rate of the corn grains decreases. However, practically, it doesn't affect heating rate of the product.

ACKNOWLEDGEMENTS

The authors would like to express their thanks to CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior, Brazil) and CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico), for its financial support to this work and also grateful to the authors of the references of this paper that it helped in the improvement its quality.

BIBLIOGRAPHIC REFERENCES


Drying of grains in cross flow conveyor dryer: a numerical solution using finite-volume method
Farias et al.
Revista Brasileira de Produtos Agroindustriais, Campina Grande, v.6, n.1, p.1-16, 2004


