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DRYING OF SILKWORM COCOON IN CROSS FLOW BELT CONVEYOR DRYER: A FINITE-VOLUME APPROACH

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Abstract. *Drying unit operation is an important process in the storage of biological materials. The cocoon produced by Bombix mori L. is a material that consists of three parts: shell, chrysalis and cast-off skin of larva. It is marketed to produce silk yarns to manufacture product with high cost. Due to high moisture content of the cocoon and low life cycle of the chrysalis it is necessary to dry these products quickly. In this sense, this paper presents a theoretical study of the drying of silkworm cocoon in multiple-band conveyor dryer. In this continuous operation system raw cocoon travel in a wire net conveyor in thin layer along of the dryer. The mathematical modeling considers variables thermo-physical properties, the influence of the porosity of the bed and transient terms in the drying and heating kinetics. The governing conservation equations were solved numerically using the finite-volume method. To examine the influence of the main drying parameters on the quality of the product in the end of the process, results of the humidity ratio and temperature of the air, and temperature and moisture content of the material along of the drying process are presented and analyzed*

Keywords: Drying, finite-volume, band conveyor, silkworm cocoon, dryer

1. Introduction

The production of silk fiber, the product of the silkworm, has been for centuries one of the chief industries of the world, especially Japan. The industry has always been divided into four independent parts: sericiculture, reeling, throwing and manufacturing. Sericiculture (silkworm culture) consist of the production of the silkworm, their care during development, and the spinning of the cocoon. There are two principal varieties of silk, the cultivated, produced by the Bombix mori, and wild silk from uncultivated moths such as the tussah.

The name Bombix mori comes from the family to which the cultivated silkworm belongs, the Bombix cidae (spinners), and mori, from the Morus multicaulis or mulberry tree, on the leaves of which it feeds.

Silkworms are cultivated by large breeders, or by small farmers, who with all their families work in the silkworm nurseries or cocooneries (Woolman and McGowan, 1943).

The life cycle of silkworm is as follows (Corbman, 1975):

a) the egg, which develops into the larva or caterpillars – the silkworm;
b) the silkworm which spins its cocoon for protection to permit development into the pupae or chrysalis;
c) the chrysalis, which emerges from the cocoon as moth;
d) the moth, of which the female lays eggs, so continuing the life cycle.

In the phase b, the silkworm begins to secrete a protein like liquid substance and with a bending motion; the filament is spun around the worm to make the cocoon. The silk filament is composed by the fibroin (two parallel filaments) and the sericin (silk gum that involves the fibroin), and rapidly harden or reaching the air. For emerge of the cocoon, the moth must break through the top of the cocoon by secreting an alkaline liquid that dissolves the filament. When this occurs, the filament cannot be unwound in one thread. If is not desirable. In order, the chrysalis is therefore killed by heating the cocoon (air or steam). If moths were allowed to break through the cocoon, the silk would be broken and spoiled for reeling.

Fresh cocoon (Fig. 1) contains live pupae, the shell and the cast-off skin of larva, and presents high initial moisture content (68-70% w.b.) in this stage. Then, it is necessary to heat the cocoon immediately after formation to kill the pupae and to remove the moisture to level down to 10-12% (d.b) for the purpose of long-term preservation and to be made as material for raw silk. One more used technique is the drying using hot-air (Shiruo, 1986; Lima e Mata, 1995).

A large variety of drying equipment (batch or continuous dryers) is currently available from manufacturers. Cocoons are dried through two techniques: fixed bed and continuous flow bed (cross-flow bed). A conveyor dryer is designed so that material is fed to continuously moving belt and it is continuously being translated horizontally, and dried on a wire net conveyor through which hot air is blown. The dry cocoon leaves the last zone and is colleted. Cocoon exposed to heat of over 110ºC for several hours in the drying chamber is affected. This thermal treatment produces injurious effects such as denaturing of the cocoons; consequently, the reelability of the silk or the raw silk properties from these cocoons may be slightly to markedly change. Heating visually recognizes color change of sericin cocoon. Changes are from white to light yellow, deep yellow, light brown, and black (around 190ºC) (Tsukada, 1978).

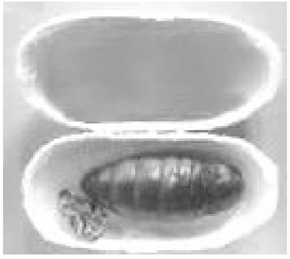

Figure 1. Cut silkworm cocoon to the half showing the chrysalis.

For the other side, a large number of the researchers have reported cross-flow dryer modeling applied to grain and seeds drying. The models consider the void fraction and/or the transient air-drying condition within the bed neglected (Bakker-Arkema 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, 2001). Other researchers present numerical study considering void fraction and/or the transient terms in the mathematical model (Eltigani & Bakker-Arkema, 1987; Vasconcelos & Alsina, 1992; França et al., 1994; Soponronnairit et al., 1996; Giner et al, 1996; Giner et al., 1998; Rumsey & Rovedo, 2001).

In order to obtain the better drying conditions and to save energy, 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 this sense, the aim of this paper is to present a theoretical study of the silkworm cocoon drying in a multiple-band conveyor dryer.

2. Materials and Methods

2.1. Mathematical modelling

The mathematical model describing continuous cross flow dryer consists of four hyperbolic partial differential equations with four unknowns (Parry, 1985) and predict the performance of the dryer.

In multi-zone cross-flow dryer (Fig. 2), air flows in the y direction and solid particles in the z direction. The length of the drier and the number of drying zone are fixed by process conditions.

The development of the conservation equation is based on the control volume illustrated in Fig. 2. How simplification of the model to describe the drying process of solids in a conveyor band dryer, the following assumptions 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.
f) The moisture evaporation takes place at the drying-air temperature.

According to assumptions, the following equations are obtained :

- Mass
  - Air

$$\frac{\partial(\rho_a x)}{\partial t} + \nabla \bullet \left(\rho_a \frac{w_a}{\varepsilon} x \right) = -\frac{\rho_P}{\varepsilon} \frac{\partial \overline{M}}{\partial t} \tag{1}$$

  - Solid

$$\frac{\partial \overline{M}}{\partial t} = f(t) \tag{2}$$

where ρ_a is the air density, x is the humidity ratio, w_a is the air velocity, ε is the porosity of the bed, ρ_p is the product density, $\overline{M}$ is the average moisture content, y is the Cartesian coordinate and t is the time.

- Energy
  - Air

$$\frac{\partial}{\partial t}(\rho_a T)+\nabla \bullet \left(\rho_a \frac{w_a}{\varepsilon} T\right)=-\frac{A^* h_c (T-\bar{\theta})}{\varepsilon(c_a + x c_v)} \qquad (3)$$

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_a and c_v are the specific heat of the air and vapor, respectively.

  - Solid

$$\frac{\partial}{\partial t}(\rho_p \bar{\theta})=\frac{A^* h_c (T-\bar{\theta})}{c_p + c_w \overline{M}}++\frac{\lfloor h_{fg} + c_v (T-\bar{\theta})\rfloor}{c_p + c_w \overline{M}} \rho_p \frac{\partial \overline{M}}{\partial t} \qquad (4)$$

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:

$$\overline{M}(y,z=0,t=0)=M_o \qquad \bar{\theta}(y,z=0,t=0)=\theta_o$$

T (y=0, z≤L/3, t) = T_1; x (y=0, z≤L/3, t) = x_1 (5a-d)

T (y=0, L/3<z≤2L/3, t) = T_2; x (y=0, L/3<z≤2L/3, t) = x_2

T (y=0, 2L/3<z≤L, t) = T_3; x (y=0, 2L/3<z≤L, t) = x_3

How application, the methodology was used to describe drying of fresh cocoons. In this sense, Lima (1995) report the following thin-layer drying equation to describe drying rate:

$$\frac{\partial \overline{M}}{\partial t}=-0.000403427e^{-0.00018984805\ t} \qquad 0 \le t \le 7200s$$
$$\frac{\partial \overline{M}}{\partial t}=-0.000175505e^{-0.00012847830\ t} \qquad 7200 < t \le 14400s \qquad (6)$$
$$\frac{\partial \overline{M}}{\partial t}=-0.00000133872e^{-0.000005738817\ t} \qquad 14400 < t \le 21600s$$

where t is in hours.

The heat of vaporization, equilibrium moisture content, surface area, volume, specific surface area, dry solid density and specific heat of the cocoon, and void fraction of the bed are given by.

$h_{fg} = 352.58(374.14 - T)^{0.33052}$ (kJ/kg) (Pakowski et al., 1991)

$c_p = 3.6\ kJ/kgK$ (Lima et al, 1997)

$\rho_P = 158.64\,kg/m^3$ (Lima, 1995) (7a-f)

$\varepsilon = 0.147$ (Lima, 1995)

$V = \frac{4}{3}\pi L_2 L_1^2$ (m^3) (Lima et al., 2002)

$$S = 2\pi L_1 L_2 \left\{ \frac{L_1}{L_2} + \frac{arcsin\left[\sqrt{\left[1-\left(\frac{L_1}{L_2}\right)^2\right]}\right]}{\sqrt{\left[1-\left(\frac{L_1}{L_2}\right)^2\right]}} \right\} \quad (m^2) \text{ (Lima et al., 2002)}$$

$$A^* = \frac{S(1-\varepsilon)}{V} = 271.71\, m^2 / m^3$$

where S and V are the surface area and volume of the cocoons, respectively. The parameters A* was obtained by considering the cocoon as an ellipsoid of revolution with dimensions to major axis L_2=2.90 cm and L_1=1.63 cm to minor axis.

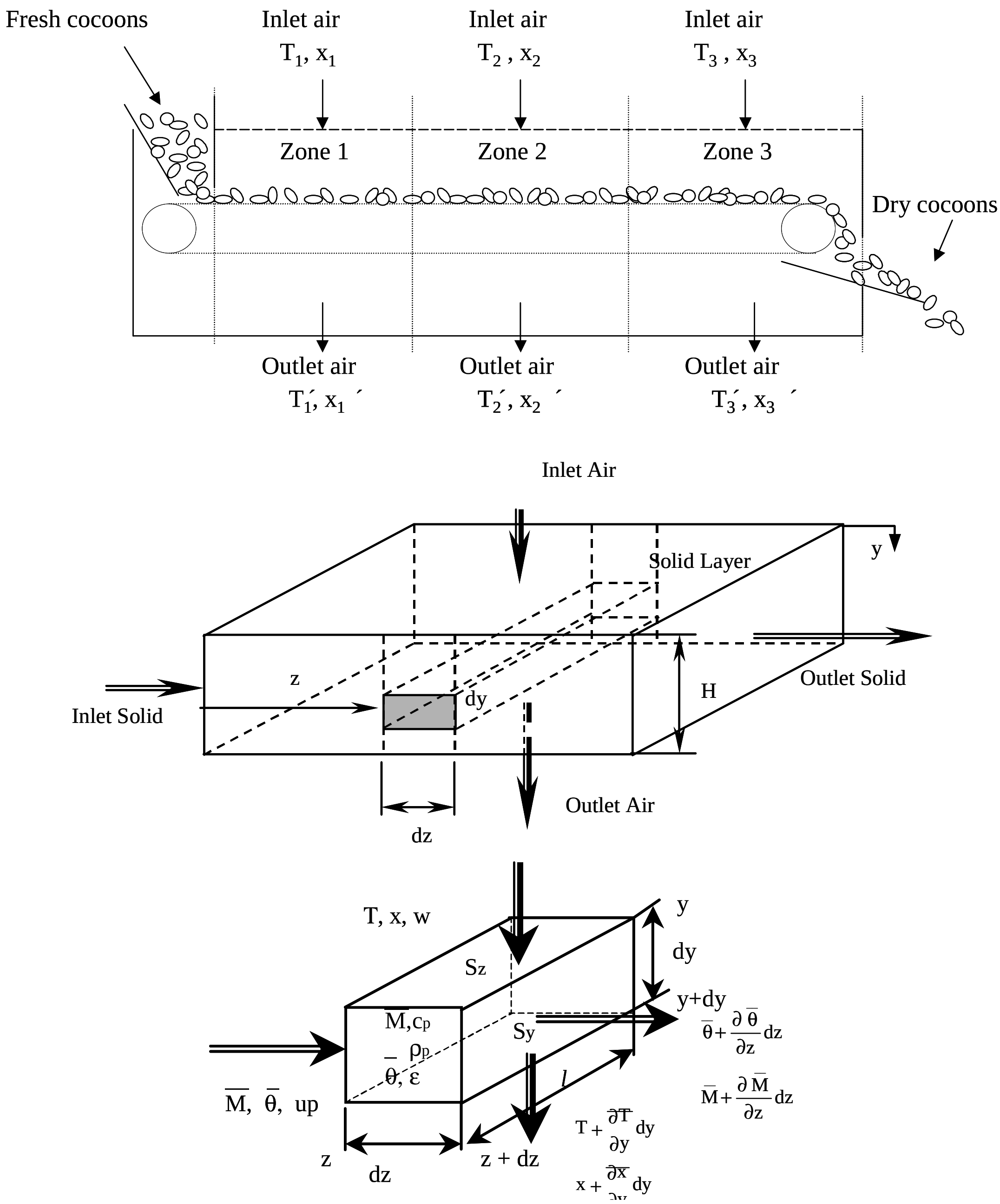

Figure 2. Schematic representation of the multi-zone cross flow belt conveyor dryer.

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

$$c_a = 1.00926 - 44.04033.10^{-5} T + 6.17596.10^{-7} T^2 - 4.0972x10^{-10} T^3 \ kJ/kgK$$

$$\rho_a = \frac{P_{atm} M_a}{R.T_{abs}} \quad (\mathrm{kg/m^3})$$

$$T_{abs} = T_a + 273.15 \ K \qquad (8a\text{-}g)$$

$$R = 8314.34 \ J/kg$$

$$P_{atm} = 101325 \ Pa$$

$$UR = \frac{P_{atm} x_a}{(x_a + 0.622).P_{vs}}$$

$$P_{vs} = 22105649.25 Exp\{[-27405.53 + 97.5413 T_{abs} - 0.146244 T_{abs}^2 + 0.12558x10^{-3} T_{abs}^3 - 0.48502x10^{-7} T_{abs}^4] / [4.34903 T_{abs} - 0.39381.10^{-2} T_{abs}]\} \quad (Pa)$$

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

$$c_v = 1.8830 - 0.16737x10^{-3} T_{abs} + 0.84386x10^{-6} T_{abs}^2 - 0.26966x10^{-9} T_{abs}^3 \quad (\mathrm{kJ/kgK}) \qquad (9a)$$

$$c_w = 2.82232 + 1.18277x10^{-2} T_{abs} - 3.5047x10^{-5} T_{abs}^2 + 3.6010x10^{-8} T_{abs}^3 \quad (\mathrm{kJ/kgK}) \qquad (9b)$$

The heat transfer coefficient was obtained using the following equations (Incropera and DeWitt, 2002):

$$h_c = (k_a / D)(2 + 0.6 Re^{1/2} Pr^{1/3}) \quad (\mathrm{W/m^{2o}C}) \qquad (10)$$

where D is the equivalent diameter of a cocoon of equal volume of an ellipsoid with dimension given above, Re and Pr are the Reynolds and Prandtl numbers of the air, respectively.

2.2 Numerical procedure

Many numerical technique 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 by integrating one under the control volume and time as illustrated in Fig. 3.

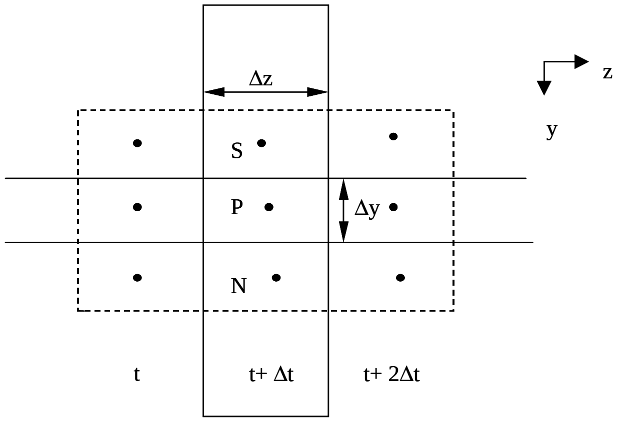

Figure 3. Control volume used in this work

The result of the integration is a set of linear equations in the discretized form as follows:

- Fresh cocoons:

  - Energy

$$A_P\bar{\theta}_P = A_P^o\bar{\theta}_P^o + S_C^{\bar{\theta}} \quad (10a)$$

where

$$A_p = \frac{\Delta z}{\Delta t_m} + \frac{h_c A^* \Delta z}{\rho_p c_p + \rho_p c_w \overline{M}} + \frac{c_v \rho_p \frac{\partial \overline{M}}{\partial t} \Delta z}{\rho_p c_p + \rho_p c_w \overline{M}}$$

$$A_P^o = \frac{\Delta z}{\Delta t_m}$$

$$S_C^{\bar{\theta}} = \frac{(h_{fg} + c_v T_p)\rho_p \frac{\partial \overline{M}}{\partial t}}{\rho_p c_p + \rho_p c_w \overline{M}} \Delta z + \frac{h_c A^* T_p \Delta z}{\rho_p c_p + \rho_p c_w \overline{M}}$$

  - Mass

$$A_P \overline{M}_P = A_P^o \overline{M}_P^o + S_C^{\overline{M}} \quad (10b)$$

where

$$A_P = \frac{\Delta z}{\Delta t_m}$$

$$A_P^o = \frac{\Delta z}{\Delta t_m}$$

$$S_C^{\overline{M}} = \frac{\partial \overline{M}}{\partial t} \Delta z$$

- Air:

  - Energy:

$$A_P T_P = A_S T_S + A_P^o T_P^o + S_C^T \quad (10c)$$

where

$$A_P = \frac{\Delta y}{\Delta t} + \frac{w_a}{\varepsilon} + \frac{A^* h_c \Delta y}{\varepsilon(\rho_a c_a + \rho_a x c_v)}$$

$$A_S = \frac{w_a}{\varepsilon}$$

$$A_P^o = \frac{A^* h_c \Delta y}{\varepsilon(\rho_a c_a + \rho_a x c_v)}$$

$$S_C^T = \frac{\Delta y}{\Delta t}$$

  - Mass:

$$A_P x_P = A_S x_S + A_P^o x_P^o + S_C^x \quad (10d)$$

where

$$A_P = \rho_a \frac{\Delta y}{\Delta t} + \rho_a \frac{w_a}{\varepsilon}$$

$$A_S = \rho_a \frac{w_a}{\varepsilon}$$

$$A_P^o = \rho_a \frac{\Delta y}{\Delta t}$$

$$S_C^x = -\frac{\rho_p}{\varepsilon} \frac{\partial \overline{M}}{\partial t} dy$$

To obtain the numerical results, a computational code using the software Mathematica® was implemented. In the equations applied to the air, the time step was evaluated by $\Delta t = \Delta y / w_a$. To the fresh cocoons, $\Delta z = u_p(npy-1)\Delta t$ and $\Delta t_m = (npy-1)\Delta t$, where npy is the nodal point number in the y-direction. During this Δt_m, the cocoons within the volume $\Delta z\, H$ were assumed stationary and thus $T, x, \overline{M}$ and $\overline{\theta}$ were obtained as for the fixed bed drying. In all equations was used upwind scheme to convective terms along the z-direction. More details about this procedure can be found in Santiago et al. (2002) and Farias (2003). No saturation was found.

3. Results and discussions

In order to analyze the effects of the air drying conditions on the moisture removal of the fresh cocoons, drying conditions for simulation are chosen according to industrial dryer conditions. Table 1 presents drying condition used in the work as well as the final moisture content, total drying time and length of the dryer.

Table 1. Air and cocoon condition used in this work, final moisture content, total drying time and length at the dryer

Silkworm cocoon			Air							L (m)
M_o (kg/kg)	H (m)	θ_o (°C)	x_1 (kg/kg)	x_2 (kg/kg)	x_3 (kg/kg)	w_a (m/s)	T_1 (°C)	T_2 (°C)	T_3 (°C)	
2.125	0.02	28.3	0.0173108	0.0173108	0.0173108	0.3	105	90	60	28.2

To validate the methodology, numerical results of the average moisture content of fresh cocoons are compared with experimental data to fixed bed and continuous drying reported in the literature (Lima, 1995). The comparison is possible because $u_p \ll w_a$ (u_p= 0.00133m/s). Figure 4 illustrates this comparison during drying process in y≈0.00 m. It is verified that good agreement was obtained.

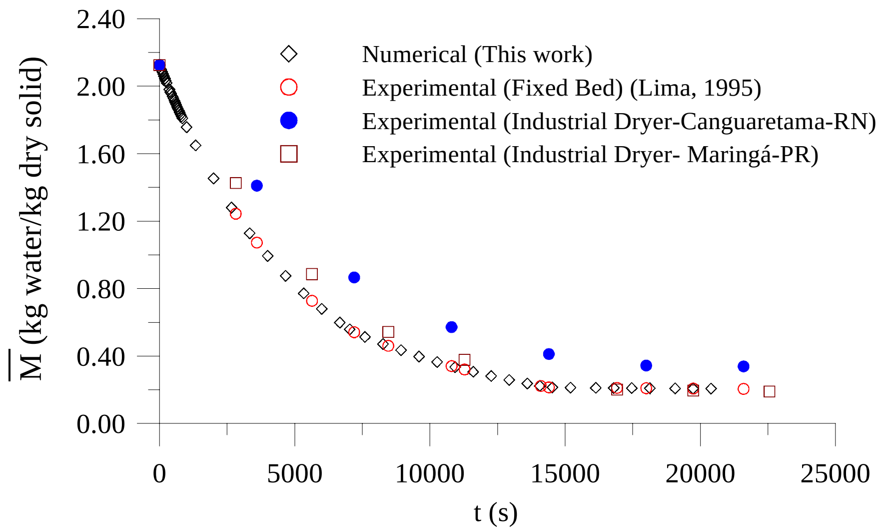

Figure 4. Comparison between the predicted and experimental values of the moisture content during drying process of fresh cocoon to H = 0.02m

Figures 5 and 6 show air and cocoon temperatures along the drying processes in each drying zone, respectively. Temperatures are reported as fractions of the drying zone. It is verified that the drying temperature has strong effect on the air temperature more than on the moisture content. However, the increase of the product temperature increases the drying rate and the cocoon reached the temperature of the air in ≈7500s because its high heat capacity. This situation may cause damage to the product quality. It is verified that as the cocoons processes through the first zone, the drying is governed by the falling drying rate because the product temperature is increasing.

Figure 7 shows the air absolute humidity (humidity ratio) within the bed along the drying. It is verified that the highest gradients occurs in the cocoons in few instants of drying and closed to entrance of the air in the dryer. Further, the high thermal gradients along the bed are not recommended because it produces non-uniform drying and big thermal stress in the cocoon. These conditions may cause change color and deformation in the solid, and to reduce its quality in the end of the process.

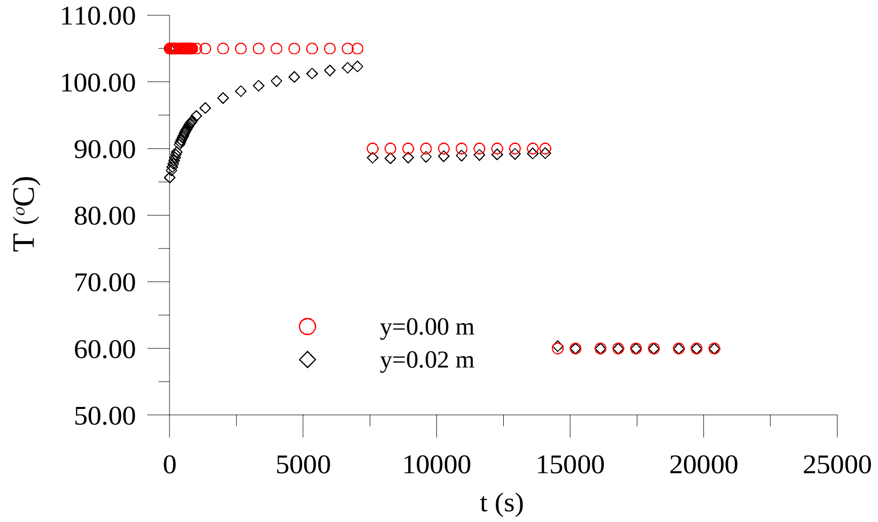

Figure 5. Air temperature within the bed during fresh cocoon drying process.

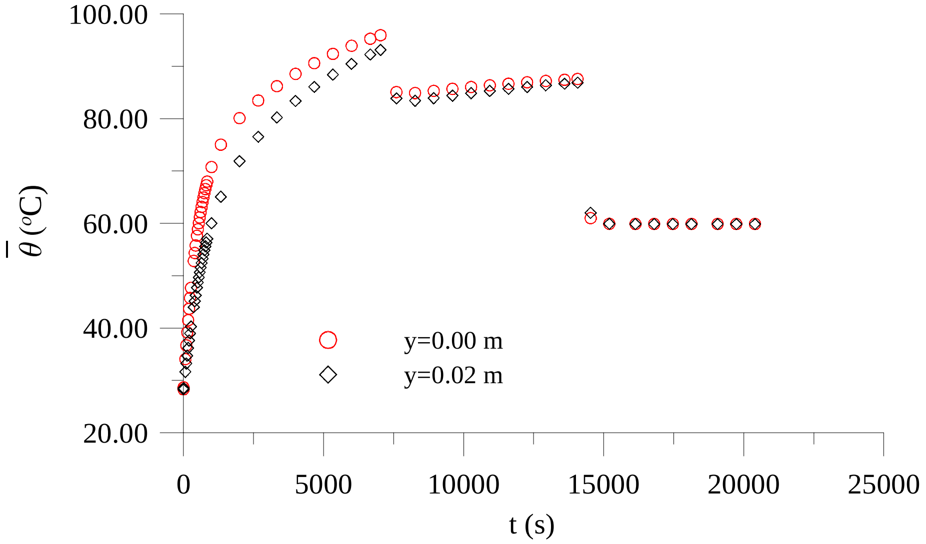

Figure 6. Cocoon temperature within the bed during drying process.

According to Lima e Mata (1996) air velocity not affect moisture removal of the cocoon. However, the temperature of cocoon is affected strongly during drying process. The increases of the airflow rate caused considerable effects on the heating rate of the product. Then the drying process is controlled by internal diffusion.

As final comment because drying is a very energy consumption process, in recent years there has been a substantial development in reducing the energy consumption in driers. This development has been moving in two directions: improvement of the actual drying processes to make them consume less energy, and improvement of heat recovery systems. In this sense, to low thickness layer of the cocoon and small relative humidity of the air in the outlet of the dryer, it can be recirculate and used to dry solid and to save energy.

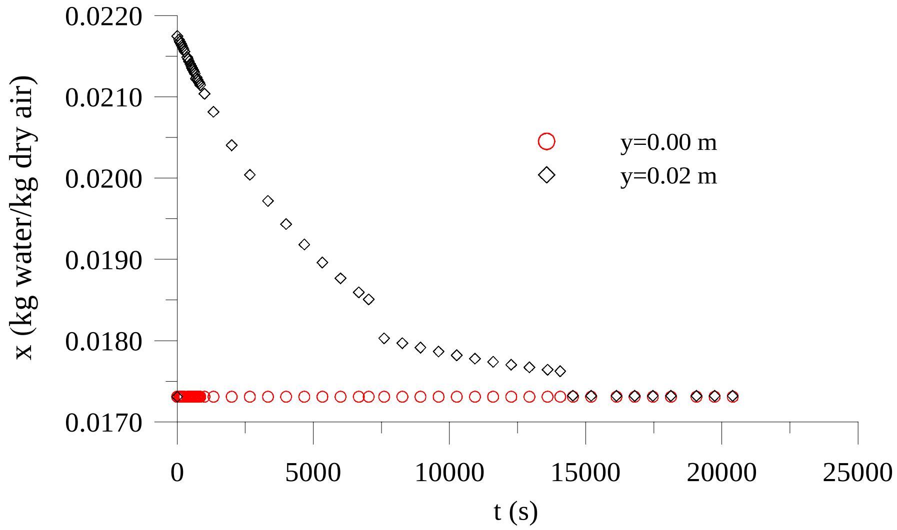

Figure 7. Air absolute humidity within the bed along drying process.

4. Conclusions

The following conclusions can be summarized:

- The finite-volume method can be used to simulate drying process in cross-flow dryer because the good agreement obtained by comparison between numerical and experimental data.
- The air temperature has effect on the drying rate of cocoon more than airflow rate.
- The mass transfer is controlled by internal diffusion, and external condition has secondary importance, because airflow rate affect not the drying rate.
- The fresh cocoon reaches the inlet air temperature in ≈7500s of elapsed drying time.
- During drying process low moisture content gradients within the bed were obtained. This is due to the small thickness layer of the grain used in the simulation.

5. Acknowledgements

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