DRYING OF SILKWORM COCOON IN CROSS FLOW BELT CONVEYOR DRYER: A NUMERICAL SIMULATION USING THE FINITE-VOLUME METHOD

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Abstract. *Drying unit operation is an important process to conservation and storage of biological materials. The cocoon produced by silkworm 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 kill it and to dry the cocoon quickly. In this sense, this paper presents a mathematical modelling to predict drying of silkworm cocoon in multiple-band conveyor dryer. The mathematical modelling considers variable 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 and the upwind scheme as interpolation function of the convective terms. 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. Numerical results of the average moisture content are compared with experimental results and good agreement was obtained. The study can be used to help researchers in the optimization of this and others types of driers under small modifications..*

Keywords*: drying, finite-volume, band conveyor, 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.

Fresh cocoon contains live pupae, the shell and the cast-off skin of larva, and contain, high initial moisture content (on average 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 (Bairamov *et al*., 1977; Gupta, 1994). One more used technique is the drying using hot-air (Tsukada, 1978; Shiruo, 1986; Shi-huo *et al*., 1992; Lima, 1995; Lima and Mata, 1996; Thangavel *et al*., 1996; Lima *et al*., 1997; Lima and Mata, 1997a; Lima *et al*.,1997b)

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 collected. Dried cocoons, after being cooled, are packed in bags to specified quantity. The multi-band type drying industrial machine has some portioned chambers (2-8) with partition plate dividing the inside of machine horizontally according to drying capacity (1000-25000 kg fresh cocoons/24 hours). Cocoon exposed to heating over 110ºC for several hours in the drying chamber is affected. This thermal treatment produces damaging effects such as denaturing of the cocoons; consequently, the real ability 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).

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 and Wood, 1991; Brokker *et al*., 1992; Fasina and Sokhansanj, 1993; Barrozo *et al*., 1996; Motta-Lima *et al*., 1996; Li *et al*., 1997; Liu and Bakker-Arkema, 2001). Other researchers present numerical studies considering void fraction and/or the transient terms in the mathematical model (Eltigani and Bakker-Arkema, 1987; Vasconcelos and Alsina, 1992; França *et al.*, 1994; Soponronnarit *et al.*, 1996; Giner *et al.*, 1996; Giner *et al.*, 1998; Rumsey and Rovedo, 2001; Farias, 2003; Farias *et al.*, 2004).

In order to obtain 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. Models development

In multi-zone cross-flow dryer (Fig. 1), 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 conservations equations is based on the control volume illustrated in Fig. 2. In order to simplify the model describing 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 solid flows are plug-type.
f) The moisture evaporation takes place at the drying-air temperature.
g) The inter-particle void fraction is constant.

According to assumptions, the following equations are obtained :

☐ Mass

- Air

$$-\frac{\partial(\rho_a w_a x)}{\partial y} - \frac{\partial(\varepsilon \rho_a x)}{\partial t} = \rho_p \frac{\partial \overline{M}}{\partial t} \qquad (1)$$

- Solid

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

☐ Energy

- Air

$$-\frac{\partial[(\rho_a w_a c_a + \rho_a w_a x c_v)T]}{\partial y} = A^* h_c (T - \overline{\theta}) + \frac{\partial[(\rho_a c_a + \rho_a x c_v \varepsilon)T]}{\partial t} \qquad (3)$$

- Solid

$$A^* h_c (T - \overline{\theta}) = (\rho_p c_p + \rho_p c_w \overline{M}).(\frac{\partial \overline{\theta}}{\partial t}) - [h^*{}_{fg} + c_v (T - \overline{\theta})] \rho_p \frac{\partial \overline{M}}{\partial t} \qquad (4)$$

where ρ is the density (kg/m^3), and subscripts “a” is the air, p is the product; ε is the porosity; $\overline{M}$ is the average moisture content kg/kg (d.b.); A^* is the specific area (m^2/m^3); c is specific heat (J/kg K); h_c is heat transfer coefficient (W/m^2 K); h_{fg} is the heat of vaporization of the product (J/kg); $\overline{\theta}$ is the solid temperature (^{o}C); T is the air temperature (^{o}C); w is velocity (m/s) and x represents the absolute humidity (kg water/kg of dry air).

The following initial and boundary conditions were used:

$\overline{M}(y, z = 0, t = 0) = M_o$ $\qquad$ $\overline{\theta}(y, z = 0, t = 0) = \theta_o$
$T\ (y=0,\ z \le L/3,\ t) = T_1$; $\qquad$ $x\ (y=0,\ z \le L/3,\ t) = x_1$ $\qquad$ (5a-d)
$T\ (y=0,\ L/3 < z \le 2L/3,\ t) = T_2$; $\qquad$ $x\ (y=0,\ L/3 < z \le 2L/3,\ t) = x_2$
$T\ (y=0,\ 2L/3 < z \le L,\ t) = T_3$; $\qquad$ $x\ (y=0,\ 2L/3 < z \le L,\ t) = x_3$

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

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

where t is in seconds.

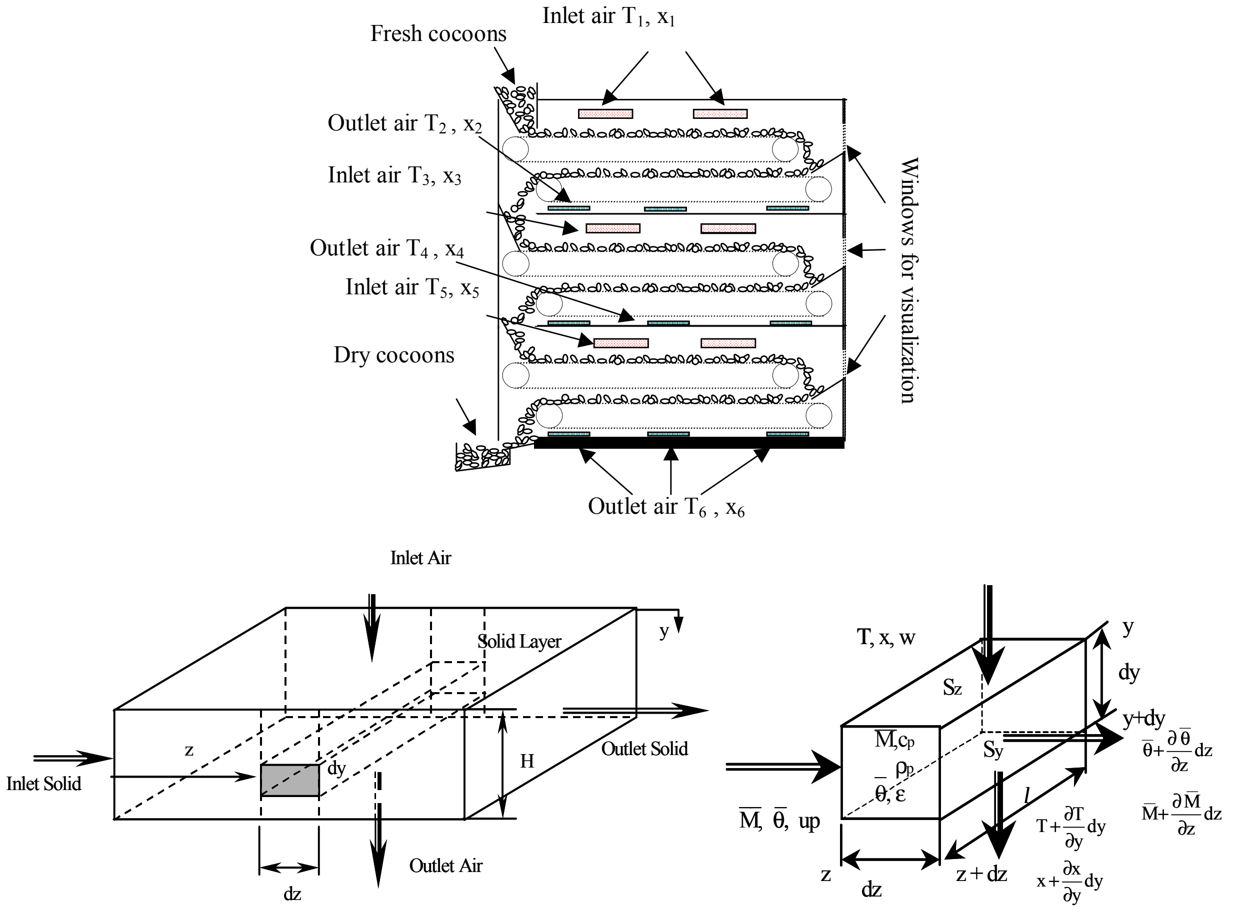

Figure 1. Schematic representation of the multi-zone cross flow belt conveyor dryer.

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

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

$c_p = 3.6\ \text{kJ/kgK}$ (Lima *et al.*, 1997)

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

$\varepsilon = 0.147$ (Lima, 1995)

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

$$S = 2\pi L_1 L_2 \left\{ \frac{L_1}{L_2} + \frac{\arcsin\left[\sqrt{\left[1-\left(\frac{L_1}{L_2}\right)^2\right]}\right]}{\sqrt{\left[1-\left(\frac{L_1}{L_2}\right)^2\right]}} \right\}$$ (m^2) (Lima *et al.*, 2002) $$A^* = \frac{S(1-\varepsilon)}{V} = 271.71\,m^2/m^3$$

where L_1, L_2 are the dimensions of the minor and major axis of the solid in m; S is the area in m^2 ; V is volume. 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 (Lima *et al.*, 2005).

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

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

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

$$\rho_a = \frac{P_{atm}M_a}{R.T_{abs}} \text{ (kg/m}^3\text{)}; \quad UR = \frac{P_{atm}x_a}{(x_a + 0.622).P_{vs}}; \qquad R = 8314.34 \text{ J/kg}; \qquad P_{atm} = 101325 \text{ Pa};$$

$$P_{vs}=22105649.25\text{Exp}\{[-27405.53 + 97.5413T_{abs} - 0.146244T_{abs}^2 + 0.12558\text{x}10^{-3}\,T_{abs}^3 - 0.48502\text{x}10^{-7}\,T_{abs}^4] / [4.34903T_{abs} - 0.39381.10^{-2}\,T_{abs}]\} \text{ (Pa)}$$

where UR is the air relative humidity; P is the pressure in Pa; The subscripts abs and atm are absolute and atmospheric respectively; R is the Universal gas constant J/(kgK)

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

$$c_v = 1.8830 - 0.16737\text{x}10^{-3}T_{abs} + 0.84386\text{x}10^{-6}\,T_{abs}^2 - 0.26966\text{x}10^{-9}\,T_{abs}^3 \quad \text{(kJ/kgK)} \qquad (9a)$$

$$c_w = 2.82232 + 1.18277\text{x}10^{-2}\,T_{abs} - 3.5047\text{x}10^{-5}\,T_{abs}^2 + 3.6010\text{x}10^{-8}\,T_{abs}^3 \quad \text{(kJ/kgK)} \qquad (9b)$$

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

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

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.

3. Numerical solution

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, 2004; Versteeg and Malalasekera, 1995). In this work, the finite-volume method was used to discretize the basic equations by integrating over the control volume and time.

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

☐ Fresh cocoons
- Energy

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

- Mass

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

☐ Air:
- Energy:

$$A_PT_P = A_ST_S + A_P^oT_P^o + S_C^T \qquad (10c)$$

- Mass:

$$A_Px_P = A_Sx_S + A_P^ox_P^o + S_C^x \qquad (10d)$$

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 $\Delta t = \Delta y / w_a$. For 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 discretized 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 an upwind scheme was used to convective terms along the z-direction. More details about this procedure can be found in Santiago *et al.* (2002) and Farias (2003). Saturation was found off air was not considered.

4. 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, and length at the dryer

Silkworm cocoon			Air							
M_o (kg/kg)	UR (m)	θ_o (ºC)	x_1 (kg/kg)	x_2 (kg/kg)	x_3 (kg/kg)	w_a (m/s)	T_1 (ºC)	T_2 (ºC)	T_3 (ºC)	L (m)
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). This comparison it is with fixed bed possible because $u_p << w_a$ (u_p= 0.00133m/s). Figure 2 illustrates this comparison during drying process in $y \approx 0.00$ m. It is verified that good agreement was obtained. In Canguaretama town, the dryer is composed by three drying chambers with the following air-temperatures ≈105, ≈ 95, and ≈ 60°C. In Maringá town the industrial dryer is composed to eight drying chamber with the following air temperature, ≈ 124, ≈ 115, ≈ 104, ≈ 98, ≈ 93, ≈ 90, ≈ 63, and ≈ 59 °C. Information about relative humidity inside dryer was not available.

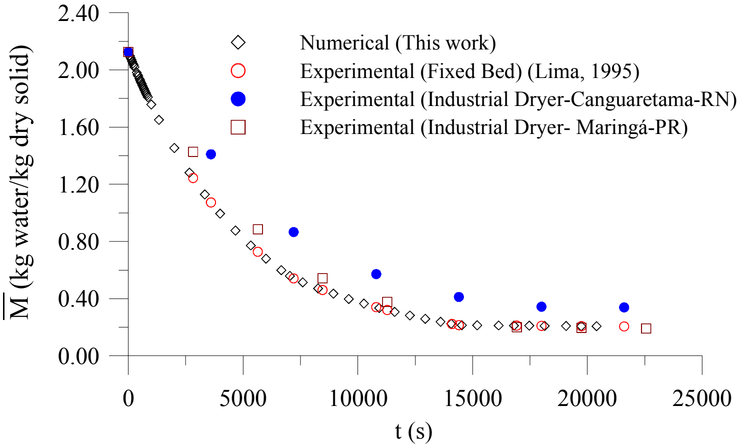

Figure 2. Comparison between the predicted and experimental values of the moisture content during drying process of fresh cocoon to H = 0.02m

Figures 3 and 4 show air and cocoon temperatures along the drying processes in each drying zone, respectively. Temperatures are reported for each drying zone. It is verified that the drying temperature has strong effect on the product temperature more than on the moisture content. However, the increase of the product temperature increases the drying rate due to the large water moisture of the product in the beginning of the process 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 5 shows the air absolute humidity (humidity ratio) within the bed along the drying process. 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.

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. Figure 5 shows the relative humidity of the air inside the bed along the drying process. It is possible to see that the relative humidity decreases in the first drying zone, increasing in the others regions dire to the increase of the air-drying temperature. The value of this parameter is lower than one during all drying process, and no saturation was found.

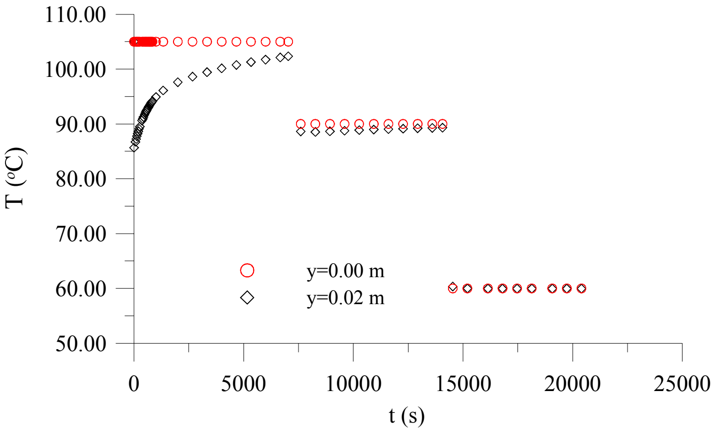

Figure 3. Air-temperature within the bed during fresh cocoon drying process.

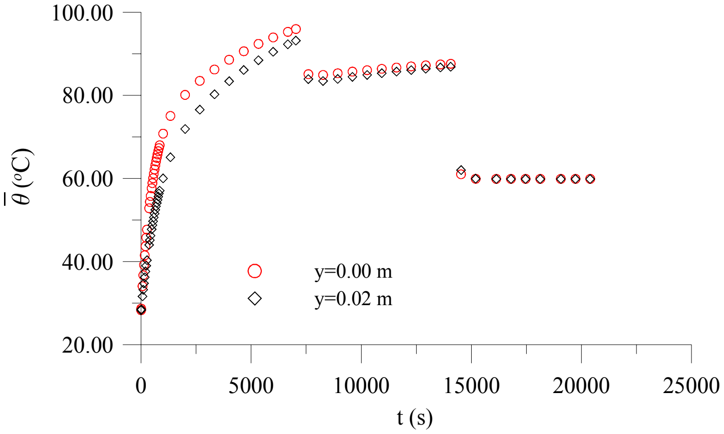

Figure 4. Cocoon temperature within the bed during drying process.

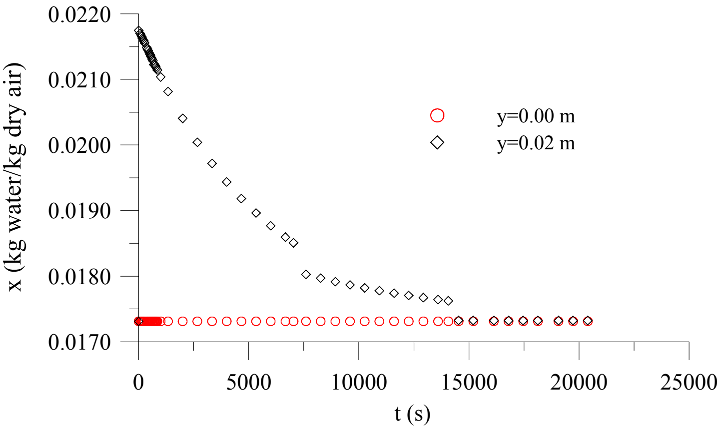

Figure 4. Air absolute humidity within the bed along drying process.

As final comment due to drying being a high energy consuming 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.

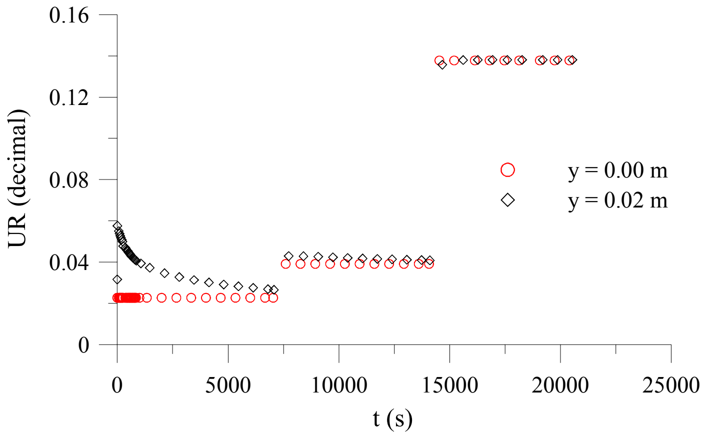

Figure 5. Air relative humidity within the bed along drying process.

5. Conclusions

The following conclusions can be summarized: The finite-volume method can be used to simulate drying process in cross-flow dryer due to the small difference existing between numerical and experimental data of the moisture content; No constant drying period was found, so, the mass transfer is controlled by internal diffusion, and external condition has secondary importance, in connection, the air temperature has effect on the drying rate of cocoon more than airflow rate; The fresh cocoon reaches the inlet air temperature in ≈7500s of elapsed drying time, and due to the small thickness layer of the bed used in the simulation, during drying process low moisture content gradients within the bed were obtained.

6. 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, Brazil) for supporting this work, and also grateful to the authors of the references of this paper that it helped in the improvement its quality.

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