Drying Technology
An International Journal
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713597247

Modeling the Drying of a Deep Bed of **Ilex paraguariensis** in an Industrial Belt Conveyor Dryer

M. E. Schmalko [a]; J. M. Peralta [ab]; S. M. Alzamora [c]
[a] Facultad de Ciencias Exactas, Químicas y Naturales, Universidad Nacional de Misiones, Posadas, Argentina
[b] Instituto de Desarrollo Tecnológico para la Industria Química, Universidad Nacional del Litoral-CONICET, Santa Fe, Argentina
[c] Departamento de Industrias, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, Ciudad Universitaria, Buenos Aires, Argentina

Online Publication Date: 01 December 2007
To cite this Article: Schmalko, M. E., Peralta, J. M. and Alzamora, S. M. (2007) 'Modeling the Drying of a Deep Bed of **Ilex paraguariensis** in an Industrial Belt Conveyor Dryer', Drying Technology, 25:12, 1967 - 1975
To link to this article: DOI: 10.1080/07373930701727317
URL: http://dx.doi.org/10.1080/07373930701727317

Drying Technology, 25: 1967–1975, 2007

ISSN: 0737-3937 print/1532-2300 online
DOI: 10.1080/07373930701727317

Taylor & Francis
Taylor & Francis Group

Modeling the Drying of a Deep Bed of *Ilex paraguariensis* in an Industrial Belt Conveyor Dryer

M. E. Schmalko,[1] **J. M. Peralta,**[1,2] **and S. M. Alzamora**[3]
[1]*Facultad de Ciencias Exactas, Químicas y Naturales, Universidad Nacional de Misiones, Posadas, Argentina*
[2]*Instituto de Desarrollo Tecnológico para la Industria Química, Universidad Nacional del Litoral-CONICET, Santa Fe, Argentina*
[3]*Departamento de Industrias, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, Ciudad Universitaria, Buenos Aires, Argentina*

The evolution of temperature and moisture content of leaves and twigs of yerba maté on different levels of a through-flow dryer was investigated by modeling heat and mass transfer using the finite-difference method. To validate the model, the temperature and moisture profiles were used to estimate chlorophyll losses.

Great variations were obtained in moisture, temperature, and chlorophyll content at different levels of the bed. Leaf temperature quickly increased in the former nodes, and it then increased slowly until it reached air temperature. In the twigs, the temperature increase was slow and the air temperature was never reached.

Keywords Chlorophyll; *Ilex paraguariensis*; Modeling belt-conveyor dryer; Moisture; Temperature

INTRODUCTION

Yerba maté or *Ilex paraguariensis* Saint Hilaire is industrially processed as whole branches. Once processed, a very popular tea can be prepared from the leaves of the plant. The processing steps are (1) heat treatment with burning propane for several minutes to inactivate enzymes, which would lead to browning of the leaves; (2) drying, carried out in two steps in a cross-flow dryer with air at 80–120°C for periods between 1.5 and 4.5 h; (3) grinding, used to prepare the material for the next step; and (4) seasoning, which is carried out in a natural way (storage for 9 months at room temperature) or a controlled way (storage in chambers at 60°C for 30–60 days).

In the drying step, the moisture content is reduced to about 5% (wet basis), equal to a water activity value of 0.3 (corresponding to the GAB monolayer moisture content at 25°C)[1] to make the leaves stable enough to allow seasoning. Changes in some components like chlorophylls, caffeine, sugars, etc., are simultaneously produced during drying. Chlorophylls are particularly important components of this product. In some countries like Brazil, an intense green color (related to a high chlorophyll levels) is preferred, while in other countries such as Argentina and Paraguay, a less intense green product (related to a low level of chlorophyll) is more accepted. To optimize the quality of dried yerba maté, it is necessary to know the variations in temperature and moisture content during the process.[1,2]

Through-flow dryers are generally used to dry yerba maté. These dryers have a perforated belt that carries the branches, while the hot gases are introduced by tubes in its lower section and are forced to pass through the bed. The moisture content and temperature of the branches and gases vary along and through the bed. The drying rate depends on air velocity and temperature, solid flow (i.e., belt velocity), and both the height and porosity of the material.[3–8] In this type of dryer the material has a fixed position on the belt, and the residence time can be considered the same for all the material. Consequently, branches can be subjected to different heat treatments according to their location. Branches situated in the lower part of the bed are put into contact with air at high temperature and low humidity while branches located in the upper part of the bed are exposed to air with low temperature and high humidity. Thus, a wide difference in moisture content, temperature, and concentration of components (like chlorophylls, sugars, and vitamins) is found at the dryer outlet in leaves and twigs situated in different positions through the bed. This difference could be very important when the bed is high, like in yerba maté dryers (approximately 1 m). In order to model chlorophyll loss, Schmalko et al.[9] studied the influence of water activity and temperature on the degradation rate of chlorophylls

---

Correspondence: M. E. Schmalko, Universidad Nacional de Misiones, Félix de Azara 1552, 3300-Posadas, Argentina; E-mail: mesh@fceqyn.unam.edu.ar

in yerba maté leaves. They found that both variables influenced the specific rate constant.

This research was aimed at evaluating the evolution of the temperature and moisture content of leaves and twigs of yerba maté at different levels in an industrial through-flow dryer by modeling heat and mass transfer. Temperature and moisture profiles were then employed to estimate chlorophyll losses and to validate the model by comparison with experimental data obtained at the factory.

MATERIALS AND METHODS

Material

Branches of yerba maté (*Ilex paraguariensis* Saint Hilaire) were used as the test material. They came from the first processing step (heat treatment with burning propane) at a factory and were transported by a belt to the dryer. Inlet branches had a mean temperature of 50°C (the range was 45–55°C), and the moisture content was very different for leaves and twigs. In leaves, this value varied between 0.14 and 0.22 w/w (dry basis), while in twigs it varied between 1.10 and 1.35 w/w (dry basis). The material was highly heterogeneous[10] with the following main characteristics:[11] both ramified and not ramified; a mean weight of 10.97 g (range: 2.5–30 g); weighted mean twig diameter of 0.0034 m (range: 0.0010–0.0100 m); and a weighted mean leaf thickness of 0.00036 m (range: 0.00020–0.00050 m).

Moisture and Chlorophyll Content Determination

Samples to determine moisture and chlorophyll contents were obtained at the dryer inlet and outlet. About 1 kg of branch material was obtained every day. Leaves were quickly separated from the twigs and both leaves and twigs were stored in separate hermetic flasks.

Moisture content was determined by drying the material in an oven at 103 ± 2°C until a constant mass was reached[1] (approximately 6 h).

Chlorophyll was quantified using an HPLC method with ultrasonic extraction of the analytes.[12,13] Ten milliliters of an acetone-water solution (85:15 in volume) were added to 1 g of sample and then sonicated for 5 min in an ultrasonic bath (Crest Ultrasonic Corporation 690 D, Trenton, NJ). An aliquot was then taken and filtered through a 0.22-µm syringe filter. The solution (10 µL) was then injected into a KNK 500 chromatograph (Konic Instruments, Barcelona, Spain) with an integrator CR3A, a UV-Vis 200 linear detector, and a C18 Altima column (250 × 4.6 mm, 5 µm of particle size). Assay conditions were as follows: the mobile phase was comprised of ethyl acetate:methanol:water (55:35:10 by volume); 2 mL/min flow and UV-Vis detection at 435 nm; 0.01 AUFS.

Calibration curves were generated by injecting chlorophylls *a* and *b* from *Algae nidulans* at concentrations varying between 0.0074 and 0.6660 mg/mL for chlorophyll *a* and between 0.0037 and 0.3330 mg/mL for chlorophyll *b*. Standards were dissolved in an acetone:water solution (85:15 by volume).[12] In order to determine the experimental error, 10 replicates of chlorophylls were determined and a variation coefficient of 7.58% was obtained.

Drying Equipment

The industrial dryer was 35 m long, 4 m wide, and 7 m high. Branches were fed at one extreme by a belt feeder and were uniformly distributed in the bed to reach a height of 1 m. The belt had two 15-m-long sections and it was perforated in order to allow air flux through. Hot gases were obtained from burning propane and were introduced into the dryer by means of five tubes in each section. The inlet gas temperature was 110°C in the first section and 100°C in the second section.

Although this model was developed for a particular industrial dryer, most commercial yerba maté dryers are similar to this one and the model could be applied to them with few changes, such as inlet temperature, bed depth, belt length, and speed.

Mathematical Model

Assumptions

The following assumptions were made in applying the differential equations for heat and mass transfer:

1. There is no temperature gradient in the solids (leaves and twigs).
2. The twigs are composite materials (xylem and bark), so an effective diffusion coefficient was used.
3. The gases are ideal.
4. The thermophysical and transport properties of the mixture of gases were calculated from the individual properties of each gas (O_2, N_2, H_2O, and CO_2).
5. The surface area varies due to shrinkage.
6. The composition of the gas phase was considered as variable and was calculated from mass balances.

Resolution Method

In order to calculate temperature and moisture content along and through the dryer, the bed was divided into 1080 volume elements or nodes by making 120 longitudinal divisions and 9 height divisions[14] (see Fig. 1). The differential equations of the energy and mass balances of the leaves, twigs, and gases were applied and the finite-difference method was used to solve them. According to this method, the properties, temperatures, and moisture content of solids and gases were considered to be constant in each node. The residence time of the solids in each node was selected as the time step to solve the equations (45 s).

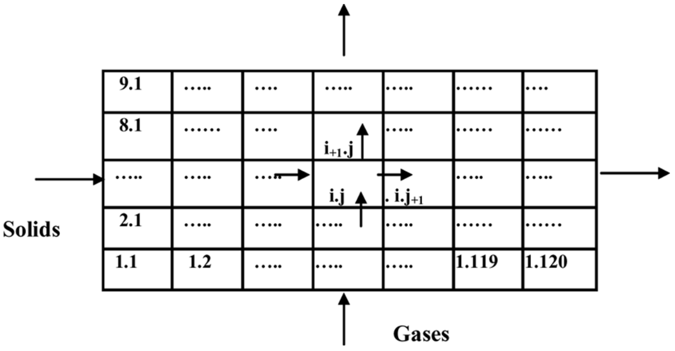

FIG. 1. Division of the solid bed in nodes.

Basic Equations: Energy Balances

The energy conservation equation at the node, for the leaves, is as follows:

$$\boxed{\text{Rate of convective heat transfer from air}} = \boxed{\text{Rate of energy consumption to water evaporation}} + \boxed{\text{Rate of accumulation of thermal energy}}$$

which has a mathematical form as follows:

$$A_l h_l(T_g - T_l) - = \lambda E_l + M_{dl}(1 + X_l)Cp_l \frac{dT_l}{dt} \tag{1}$$

Reordering Eq. (1), an expression of temperature variation can be obtained:

$$\frac{dT_l}{dt} = \frac{1}{M_{dl}(1 + X_l)Cp_l}[A_l h_l(T_g - T_l) - \lambda E_l] \tag{2}$$

Considering a finite difference of time Δt, the change in leaf temperature in the node can be calculated using the following equation:

$$\Delta T_l = \frac{\Delta t}{M_{dl}(1 + X_l)Cp_l}[A_l h_l(T_g - T_l) - \lambda E_l \tag{3}$$

In the same way, the changes in temperature for the twigs can be calculated with the following equation:

$$\Delta T_t = \frac{\Delta t}{M_{dt}(1 + X_t)Cp_t}[A_t h_t(T_g - T_t) - \lambda E_t] \tag{4}$$

For the gases, the energy conservation equation at the node is as follows:

$$\boxed{\text{Rate of accumulation of thermal energy}} = - \boxed{\text{Rate of convective heat transfer to leaves}} - \boxed{\text{Rate of convective heat transfer to twigs}} + \boxed{\text{Rate of energy entrance from leaf vapour}} + \boxed{\text{Rate of energy entrance from twig vapour}}$$

which is mathematically expressed as:

$$\begin{aligned} M_{dg}(1 + Y_g)Cp_g \frac{dT_g}{dt} = & -A_l h_l(T_g - T_l) - A_t h_t(T_g - T_t) \\ & + E_l Cp_l(T_g - T_l) + E_t Cp_t(T_g - T_t) \end{aligned} \tag{5}$$

Reordering Eq. (5), an expression of temperature variation can be obtained:

$$\begin{aligned} \frac{dT_g}{dt} = & \frac{-1}{M_{dg}(1 + Y_g)Cp_g}[A_l h_l(T_g - T_l) + A_t h_t(T_g - T_t) \\ & + E_l Cp_l(T_l - T_g) + E_t Cp_t(T_t - T_g)] \end{aligned} \tag{6}$$

Considering a finite difference of time Δt, the change in leaf temperature in the node can be calculated using the following equation:

$$\begin{aligned} \Delta T_g = & \frac{-\Delta t}{M_{dg}(1 + Y_g)Cp_g}[A_l h_l(T_g - T_l) + A_t h_t(T_g - T_t) \\ & + E_l Cp_l(T_l - T_g) + E_t Cp_t(T_t - T_g)] \end{aligned} \tag{7}$$

Temperatures for the nodes close to $i \cdot j$ can be calculated in the following way: $T_{l,i\cdot j} + \Delta T_l$; $T_{t,i\cdot j+1} = T_{t,i\cdot j} + \Delta T_t$ and $T_{g,i\cdot j} + 1 = T_{g,i\cdot j} + \Delta T_g$.

Mass Transfer

Water transfer to the air was calculated using the integrated equation of Fick's second law, but the external resistance to mass transfer was considered in the diffusion coefficient (D^*). In order to calculate this coefficient, two resistances to mass transfer (solid and air) and the equilibrium in the interphase were considered. For leaves:

$$\boxed{\text{Global resistance to mass transfer}} = \boxed{\text{Solid resistance to mass transfer}} + \boxed{\text{Gas resistance to mass transfer}}$$

which has a mathematical form as follows:

$$\frac{L(1 + X_l)}{4\rho_s D_l^*} = \frac{L(1 + X_l)}{4\rho_s D_l} + \frac{m'}{k_{Gl} Y \rho_G} \tag{8}$$

Reordering the equation yields:

$$D_l^* = \frac{L(1 + X_l)}{4\rho_s} * \frac{1}{\frac{L(1+X_l)}{4\rho_s D_l} + \frac{m'}{k_{Gl} Y \rho_G}} \tag{9}$$

For twigs, the following equation was obtained:

$$D_t^* = \frac{d(1 + X_t)}{4\rho_s} * \frac{1}{\frac{d(1+X_t)}{4\rho_s D_{ef}} + \frac{m'}{k_{Gt} Y \rho_G}} \tag{10}$$

where D_{ef} is the effective diffusion coefficient of the twig (see Table 1). In this equation the resistances of the bark and xylem were considered as two resistances in series.[15] A similar approach was recently published by Martynenko[16] working on ginseng root. In that paper, as in this case, a model with three resistances in series was considered (core, skin, and air).

TABLE 1
Solid properties and coefficients used in the model

Parameter	Reference
$Cp_l = 1.539 \cdot 10^3 + 2.72 \cdot 10^3 \frac{X_l}{(1+X_l)}$	[19]
$Cp_t = 1.79 \cdot 10^3 + 2.36 \cdot 10^3 \frac{X_t}{(1+X_t)}$	[20]
$\lambda = 7020 - 803 \ln(T)$	[24]
$\rho_l = 560 + 187X_l \qquad \rho_t = 701 + 730X_t$	[19], [20]
$L_l = 2.6 \cdot 10^{-4} + 6.34 \cdot 10^{-5} X_h$	[19]
$s_t = \dfrac{0.613 + 0.192X_t}{0.613 + 0.192X_{t0}}$	[20]
$D_l = 6.64 \cdot 10^{-6}(1 + X_l)e^{\left[\frac{-3733}{T_l}\right]}$	[19]
$D_{tX} = 1.24 \cdot 10^{-7}(1 + 0.75X_p)e^{\frac{-2270}{T_p}} e^{412R_i}$	[15]
$D_{tB} = 9.95 \cdot 10^{-5}(1 + 0.28X_p)e^{\frac{-5968}{T_p}} e^{936R_0}$	
$D_{ef} = \dfrac{1}{\frac{(d_B - d_x)}{d_B}\frac{1}{D_{tB}} + \frac{1}{mD_{tx}}}$	

m = Slope of the equilibrium line between xylem and bark.

For leaves, the integrated equation for an infinite plane plate was used:[17]

$$\frac{X_l - X_{le}}{X_{l0} - X_{le}} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}e^{\left[\frac{-(2n+1)^2\pi^2 D_l^* t}{L^2}\right]} \tag{11}$$

Considering the first term of the sum and the equation for $X_{l,i\cdot j+1}$ and $X_{l,i\cdot j}$, and determining making the difference between these two equation, the following equation was obtained:

$$\frac{X_{l,i\cdot j+1} - X_{le}}{X_{l,i\cdot j} - X_{le}} = e^{\left[\frac{-\pi^2 D_l^* \Delta t}{L^2}\right]} \tag{12}$$

For twigs, the integrated equation for an infinite cylinder with radial transfer was used:[17]

$$\frac{X_t - X_{te}}{X_{t0} - X_{te}} = \sum_{n=1}^{\infty}\frac{4}{\mu_n^2}e^{\left[\frac{-\mu_n^2 D_t^* t}{R_0^2}\right]} \tag{13}$$

Considering the first term of the sum and considering the equation for $X_{t,i\cdot j+1}$ and $X_{t,i\cdot j}$, and determining the difference between these two equation, the following expression was obtained:

$$\frac{X_{t,i\cdot j+1} - X_{te}}{X_{t,i\cdot j} - X_{te}} = e^{\left[\frac{-2.4048^2 D_t^* \Delta t}{r^2}\right]} \tag{14}$$

The rate of water evaporation from leaves can be calculated as: $E_l = M_{dl}(X_{l,i\cdot j} - X_{l,i\cdot j+1}) * \Delta t$; and for twigs $E_t = M_{dt}(X_{t,i\cdot j} - X_{t,i\cdot j+1}) * \Delta t$.

Gas humidity was calculated from the equation:

$$Y_{i+1\cdot j} = Y_{i\cdot j} + \frac{E_l + E_t}{M_{dg}} * \Delta t \tag{15}$$

Chlorophyll Losses

In order to estimate chlorophyll losses, a first order kinetics equation was considered (Eq. (16)). The specific constant rate was calculated at the predicted temperature and moisture content in each node, using kinetic parameters previously obtained by Schmalko et al.[9]

$$\ln\left(\frac{C}{Co}\right) = -k_d(\mathrm{T}, \mathrm{X})t \tag{16}$$

Fit of the Model

In order to evaluate the fit of the model, the root mean square error (RMSE) was calculated using the following equation:

$$\mathrm{RMSE} = \left[\frac{1}{\mathrm{N}}\sum(\mathrm{X}_{\mathrm{exp}} - \mathrm{X}_{\mathrm{calc}})^2\right]^{0.5} \tag{17}$$

Properties

The gas properties and heat and mass transfer coefficients used in the model are shown in Table 2. The mean composition of the gas was used to calculate the convective heat and mass transfer coefficients. The solid properties and coefficients used in the model are shown in Table 1. Leaf properties were obtained from previous research.[18,19] To estimate the diffusion coefficient of the water and other properties, the twigs were considered as a composite material (xylem and bark).[15,20] In this work, experiments were carried out between 70 and 130°C. Each material was found to have a different dependence of the parameters on moisture content and temperature (Table 1).

RESULTS AND DISCUSSION

Working Conditions

Working conditions at the factory were obtained from measurements made on seven different days. A solid flow rate was obtained from production data. The other variables were mean values of measurements taken twice daily during the seven days. These variables were as follows:

Inlet Conditions

- branch flow rate: 0.422 kg dry solids/s;
- leaf flow rate: 0.282 kg dry solids/s;
- twig flow rate: 0.140 kg dry solids/s;
- air flow rate: first section: 4.04 kg dg/s; second section: 4.07 kg dg/s;
- absolute humidity of the air: 0.0156 kg water/kg dry air;

TABLE 2
Gas properties and coefficients used in the model

Parameter	Reference
$k_m = \sum_{i=1}^{n} \frac{y_i k_i}{\sum_{j=1}^{n} y_j A_{ij}}$	[23], p. 2.368
$S_i = 1.5T_{bi} \quad S_{ij} = S_{ji} = (S_i S_j)^{0.5}$ $A_{ij} = 0.25\left\{1 + \left[\frac{\mu_i}{\mu_j}\left(\frac{M_j}{M_i}\right)^{0.75}\left(\frac{T+S_i}{T+S_j}\right)\right]^{0.5}\right\}^2\left(\frac{T+S_{ij}}{T+S_i}\right)$	
$\mu_m = \sum_{i=1}^{n} \frac{\mu_i}{\left[1 + \sum_{j=1}^{n}\left(Z_{ij}\frac{y_j}{y_i}\right)\right]} \qquad Z_{ij} = \frac{\left[1 + \left(\frac{\mu_i}{\mu_j}\right)^{0.5}\left(\frac{M_j}{M_i}\right)^{0.25}\right]^2}{\sqrt{8}\left(1 + \frac{M_i}{M_j}\right)^{0.5}}$	[23], p. 2.363
$Cp_g = \sum_{i=1}^{n} y_i Cp_i$	[23], p. 2.347
$h_h = 0.205\left(\frac{k_g}{L}\right)\mathrm{Re}_L^{0.588}\ \mathrm{Pr}^{1/3}$	[23], p. 5.15
$h_t = 0.51\left(\frac{k_g}{d}\right)\mathrm{Re}_d^{0.5}\ \mathrm{Pr}^{0.37}$	[25], p. 455
$k_{Gt} = 0.74\frac{D_g\rho_g}{d}\left(\frac{vd}{\nu}\right)^{0.5}\left(\frac{\nu}{D_g}\right)^{1/3}$	[23], p. 5.65
$k_{Gl} = 0.0365\frac{D_g\rho_g}{L}\left(\frac{vL}{\nu}\right)^{0.8}$	[23], p. 5.60

- solids temperature: 50°C;
- air temperature: first section: 110°C; second section: 100°C.

Outlet Conditions

- absolute humidity of the air: 0.0367 kg water/kg dry air and air temperature: 50°C.

Others

- belt speed: 0.055 m/s
- mean residence time of the branches: 5400 s
- height of the bed: 1 m
- air rate at the bed inlet: 0.08 m/s

The mean moisture contents of leaves and twigs measured on seven different days and used to compare experimental and predicted data are shown in Table 3.

Application of the Model

Temperature

Figure 2 shows the temperature evolution of the leaves. In the low levels of the bed, temperature increased significantly in the former nodes and then increased slowly until it reached the air temperature in the first section. Then, the temperature decreased due to an air inlet temperature reduction from 110 to 100°C and remained constant until the end of the dryer. In twigs, the increase in temperature was slower than in leaves (Fig. 3). This difference could be explained considering that: (1) heat transfer area per volume was approximately 10 times higher in leaves than in twigs and (2) the inlet moisture content of twigs was higher than that of leaves and, consequently, water loss was higher. Because of these two reasons, the twigs temperature did not reach air temperature.

TABLE 3
Average inlet and outlet experimental moisture content (in kg w/kg ds) of leaves (X_l) and twigs (X_t) measured on seven different days

	X_l		X_t	
Day	Inlet	Outlet	Inlet	Outlet
1	0.2112	0.0594	1.3100	0.3633
2	0.1476	0.0390	1.2821	0.3477
3	0.1979	0.0948	1.1777	0.4102
4	0.2066	0.0791	1.1210	0.4447
5	0.1975	0.0710	1.0978	0.3649
6	0.1617	0.0500	1.1119	0.4965
7	0.2118	0.0740	1.3507	0.3439
Mean value	0.1906	0.0668	1.2073	0.3958

Moisture Content

At the lower levels, the evolution of the moisture content of leaves exhibited the typical pattern of drying curves (Fig. 4), but at the higher levels the variation was lower. No changes in the pattern of variation of moisture content were observed when leaves entered the second dryer section at a lower temperature. This could be explained considering that in the lower levels moisture contents were too low while minor changes in air temperature occurred in the upper levels. The moisture content of the different levels had low variations at the extreme outlet (between 0.01 and 0.07 kg w/kg ds). The variations in the moisture content of twigs at the different levels were greater than those in leaves (Fig. 5). At the extreme outlet, differences in moisture content between 0.03 and 0.50 kg w/kg ds were found.

Table 4 shows the mean values of predicted and experimental moisture content in leaves and twigs and the root mean square error (RMSE). Predicted values of leaf moisture content were always lower than the experimental ones. Some moisture transfer from twigs to leaves could be expected because of the great difference in moisture content between them. The RMSE was greater in twigs than in leaves because the absolute value of moisture content in twigs was greater than in leaves.

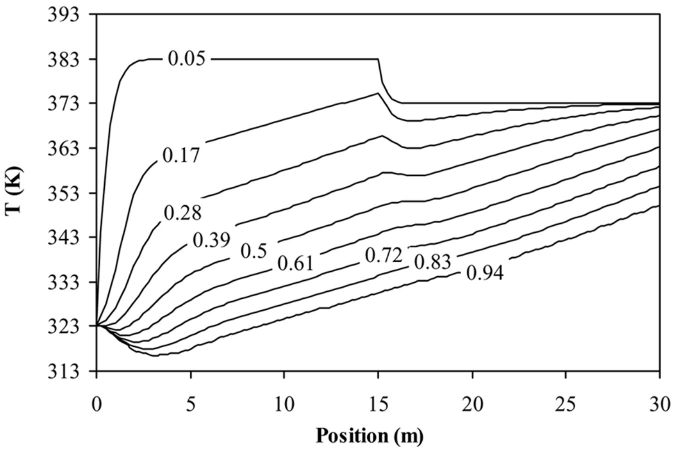

FIG. 2. Predicted temperature of leaves at different levels of the bed.

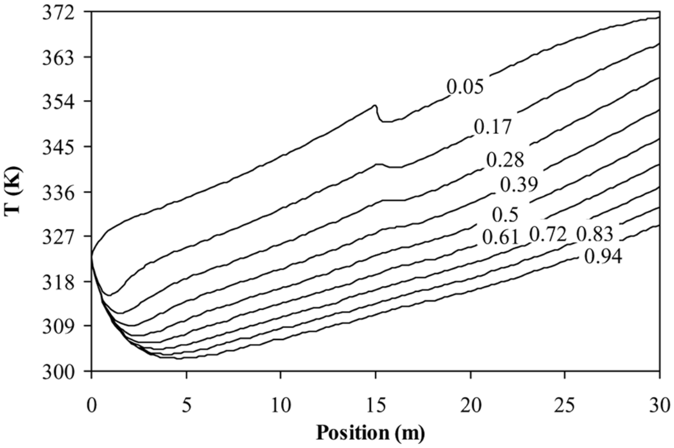

FIG. 3. Predicted temperature of twigs at different levels of the bed.

Chlorophyll Content

Variation in chlorophyll content (a and b) at the different levels of the bed was also predicted. First, the specific rate constant (k_d) was calculated considering leaf temperature and moisture content at each node.[9] Then, using a first order rate equation (Eq. (16)) and considering the time step, the concentration relationship (C/C_0) was evaluated. The specific rate constant increased with the increase of temperature and moisture content.[9] Predicted values for chlorophyll a retention are shown in Fig. 6.

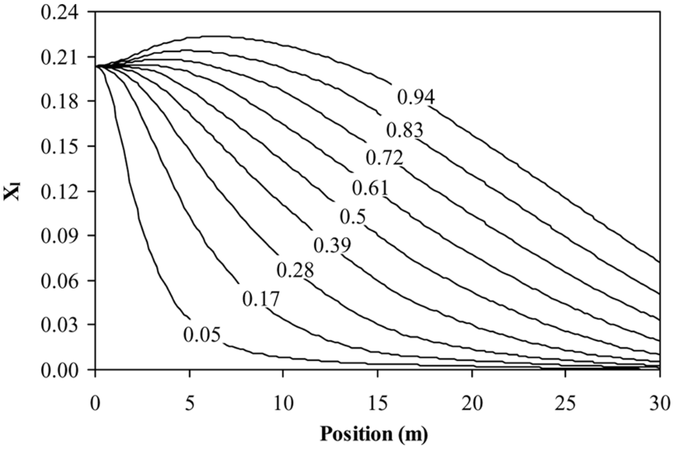

FIG. 4. Predicted moisture content of leaves (in kg w/kg ds) at different levels of the bed.

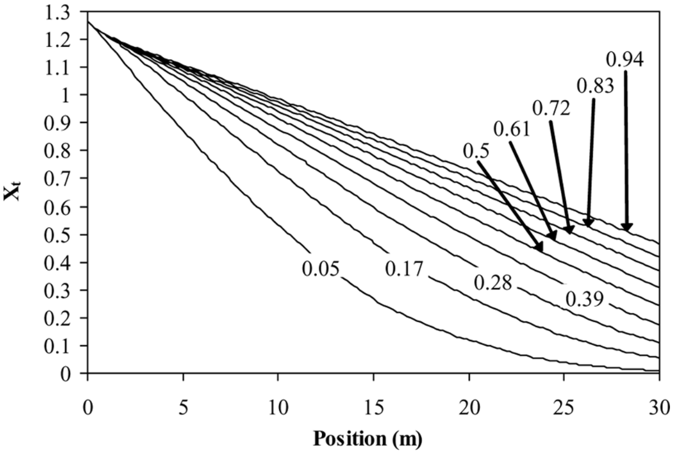

FIG. 5. Predicted moisture content of twigs (in kg w/kg ds) at different levels of the bed.

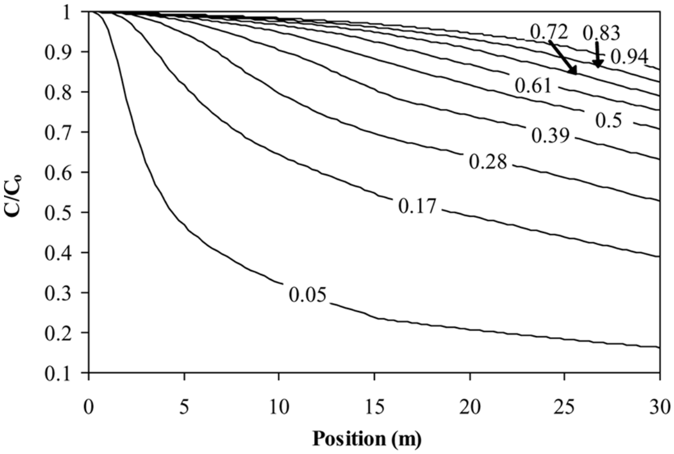

FIG. 6. Predicted chlorophyll *a* content (C/C_0) at different levels of the bed.

Changes in chlorophyll *b* presented a similar behavior. The degradation was higher at the lower levels of the bed, where the temperature was higher and the moisture content was lower. At those levels, the degradation was four times greater than in the higher ones. Experimental and predicted mean values at the dryer outlet (for 7 experiments) were 0.774 and 0.733 g/kg ds for chlorophyll *a* and 0.138 and 0.185 g/kg ds for chlorophyll *b*. The predicted mean value of C/C_0 was 0.48 for chlorophyll *a* and 0.82 for chlorophyll *b* in experiment 1. Values of C/C_0 in the other experiments did not differ significantly from these values.

Variation of Inlet Gas Temperature

In order to evaluate the response of twig and leaf moisture content and chlorophyll loss, a simulation of the dryer was conducted using different inlet gas temperatures. In all cases, similar energy consumption was considered. Results are shown in Table 5. As can be observed, the conditions for minimum of chlorophyll losses (condition 3 for chlorophyll *a* and condition 4 for chlorophyll *b*) are not the same as the conditions for maximum moisture loss (condition 8). Generally, it is recommended to operate the dryer at the maximum temperature during the initial steps of drying.[21,22] The simulation results do not agree with this recommendation because the higher drying rate is obtained with a temperature equal to 90°C at the first step and 120°C at the second step (less moisture content). This disagreement is probably due to the fact that the leaves and twigs are partially dried in the previous step and that the inlet solid temperature is relatively high (50°C). It should also be mentioned that the outlet air never reached its humidity saturation.

TABLE 4
Mean moisture content (in kg w/kg ds) at the outlet of the dryer (experimental and predicted values) and the root mean square error (RMSE)

	X_l		X_t	
Day	Experimental	Predicted	Experimental	Predicted
1	0.0594	0.0493	0.3633	0.4446
2	0.0390	0.0302	0.3477	0.3882
3	0.0948	0.0432	0.4102	0.4169
4	0.0791	0.0342	0.4447	0.3109
5	0.0710	0.0301	0.3649	0.2906
6	0.0500	0.0230	0.4965	0.2798
7	0.0740	0.0527	0.3439	0.4796
Mean value	0.0668	0.0375	0.3958	0.3729
RSME		0.0033		0.1178

CONCLUSIONS

When a simulation of a belt conveyor dryer was applied to the drying of yerba maté branches, great variations were found in moisture content, temperature, and chlorophyll content at the different levels of the bed. Losses of chlorophylls in the lower levels were about four times greater than in the higher levels.

In leaves at the lower levels, temperature quickly increased in the former nodes and then increased slowly until it reached air temperature. In the twigs, the temperature increase was slower and they never reached air temperature.

Predicted values of leaf moisture content were always less than the experimental values. Some moisture transfer from twigs to leaves can be expected because of the great difference in moisture content between them. The predicted values of moisture and chlorophyll content had a good agreement with the experimental values (values of RSME for moisture content were lower than 0.1178 for twigs and 0.0033 for leaves).

TABLE 5
Dryer simulation with different gas inlet temperatures

Condition	T_{g1}	T_{g2}	X_l	X_t	C/C_0 *a*	C/C_0 *b*
1	125	85	0.0619	0.4781	46.78	80.39
2	120	90	0.0563	0.4657	47.41	81.26
3	115	95	0.0521	0.4546	47.69	81.80
4*	**110**	**100**	**0.0493**	**0.4446**	**47.54**	**81.94**
5	105	105	0.0475	0.4363	46.97	81.69
6	100	110	0.0463	0.4304	45.92	81.02
7	95	115	0.0456	0.4267	44.40	79.87
8	90	120	0.0457	0.4254	42.58	78.31
9	85	125	0.0465	0.4265	40.47	76.11

*Condition 4 corresponds to experiment 1 of Table 4, in which the experimental values were $X_l = 0.0594$ kg w/k ds, $X_t = 0.3633$ kg w/k ds, C/C_0 for chlorophyll $a = 44.61\%$ and C/C_0 for chlorophyll $b = 86.53\%$. T_{g1} and T_{g2} were the inlet gas temperatures of sections 1 and 2, respectively.

NOMENCLATURE

A	Mean surface transfer area (m^2)
A_{ij}	Coefficient used to calculate thermal conductivity
A_t	Mean surface area of twigs in the node (m^2)
A_l	Mean surface area of leaves in the node (m^2)
C	Chlorophyll content (g/kg of dry solid)
Cp	Specific heat capacity (J/kg K)
D	Water diffusion coefficient (m^2/s)
D_g	Water diffusion coefficient in the gas phase (m^2/s)
d	Twig diameter (m)
ds	Dry solid
E	Evaporated water in the node (kg/s)
h	Convective heat transfer coefficient (J/m^2 K)
k	Thermal conductivity (J/m K)
k_d	Specific rate constant of chlorophyll degradation (h^{-1})
k_G	Mass transfer coefficient (kg/m^{2}s)
L	Leaf thickness (m)
M	Molecular weight (g/mol)
M_{dg}	Dry mass of gases in the node (kg)
M_{dl}	Dry mass of leaves in the node (kg)
M_{dt}	Dry mass of twigs in the node (kg)
m	Slope of the sorption isotherm[23]
Pr	Prandtl number
Re	Reynold's number
Ri	Xylem twig radius (m)
Ro	External twig radius (m)
S_{ij}	Coefficients used to estimate thermal conductivity
s	Shrinkage coefficient
T	Temperature (K)
T_b	Normal boiling temperature (K)
t	Time (s)
w	Water
X	Moisture content (kg water/kg dry solid)
Y	Absolute gas humidity (kg water/kg dry gas)
y	Molar fraction of gases
Z	Coefficient used to estimate viscosity

Greek Letters

λ	Evaporation latent heat (J/kg)
μ	Gas viscosity (kg/m s)
μ_{n}	Roots of Bessel functions of the first kind and zero order
ρ	Density (kg/m^3)
μ	Gas viscosity (kg/m s)
μ_{n}	Roots of Bessel functions of the first kind and zero order

Subscripts

B	Bark
cal	Calculated
d	Dry
e	Equilibrium
ef	Effective
exp	Experimental
g	Gases
l	Leaves
m	Mean
o	Initial
t	Twig
X	Xylem

REFERENCES

1. Schmalko, M.E.; Alzamora, S.M. Color, chlorophyll, caffeine and water content variation during yerba matè processing. Drying Technology **2001**, *19*, 599–610.
2. Pasardi, R.L.; Schvezov, C.E.; Schmalko, M.E.; Gonzalez, A.D. Drying of *Ilex paraguariensis* Saint Hilaire by microwave radiation. Drying Technology **2006**, *24*, 1437–1442.
3. Giner, S.A.; Mascheroni, S.H.; Nellist, M.E. Cross-flow drying of wheat: A simulation program with a diffusion-based deep-bed model and a kinetic equation for viability loss estimation. Drying Technology **1996**, *14*, 2255–2292.

4. Khankari, K.K.; Patankar, S.V. Performance analysis of a double deck conveyor dryer—A computational approach. Drying Technology **1999**, *17*, 2055–2067.
5. Madhiyanon, T.; Soponronnarit, S.; Tia, W. A two-region mathematical model for batch drying of grains in a two-dimensional spouted bed. Drying Technology **2001**, *19*, 1045–1064.
6. Sitompul, J.P.; Sumardiono, S. Modeling and simulation of a momentum, heat, and mass transfer in a deep-bed grain dryer. Drying Technology **2003**, *21*, 217–229.
7. Dimitriadis, A.N.; Akritridis, C.B. A model to simulate chopped alfalfa drying in a fixed deep bed. Drying Technology **2004**, *22*, 479–490.
8. Erriguible, A.; Bernada, P.; Couture, F.; Roques, M.A. Modeling of heat and mass transfer at the boundary between porous medium and its surroundings. Drying Technology **2005**, *23*, 455–472.
9. Schmalko, M.E.; Scipioni, P.G.; Ferreyra, D.J. Effect of water activity and temperature in color and chlorophylls changes in yerba maté leaves. International Journal of Food Properties **2005**, *8*, 313–322.
10. Coelho, G.C.; Araujo, M.J.E.; Schenkel, E.P. Population diversity on leaf morphology of maté (*Ilex paraguariensis* St.-Hil., Aquefoliaceae). Brazilian Archives of Biology and Technology **2002**, *45*, 47–51.
11. Peralta, J.M.; Schmalko, M.E. Modeling heat and mass transfer in the heat treatment step of yerba maté processing. Brazilian Journal of Chemical Engineering **2007**, *24*, 73–82.
12. Morawicki, R.O.; Schmalko, M.E.; Känzig, RG. Chlorophyll stability in yerba maté leaves in controlled atmospheres. Brazilian Archives of Biology and Technology **1999**, *42*, 85–90.
13. Ryan-Stoneham, T.; Tong, C.H. Degradation kinetics of chlorophyll in peas as a function of pH. Journal of Food Science **2000**, *65*, 1296–1302.
14. Hoffman, J.D. *Numerical methods for Engineers and Scientists*; McGraw Hill: New York, 1992.
15. Schmalko, M.E.; Alzamora, S.M. Modeling the drying of a twig of "yerba matè" considering as a composite material: Part II: Mathematical model. Journal of Food Engineering **2005**, *67*, 267–272.
16. Martynenko, A.I. Evaluation of mass transfer resistances from drying experiments. Drying Technology **2006**, *24*, 1569–1582.
17. Suarez, C.; Chirife, J.; Viollaz, P. Shape characterization for a simple diffusion analysis of air drying of grains. Journal of Food Science **1981**, *47*, 97–100.
18. Schmalko, M.E.; Alzamora, S.M. Modeling the drying of a twig of yerba maté considering as a composite material: Part I: Shrinkage, apparent density and equilibrium moisture content. Journal of Food Engineering **2005**, *66*, 455–461.
19. Perry, R.H.; Green, D.W. *Perry's Chemical Engineers' Handbook*, 7th ed.; McGraw Hill, New York, NY, 1997.
20. Kreith, F.; Bohn, M. *Principles of Heat Transfer*, 5th Ed.; West Publishing Company, St. Paul, MN, 1997.
21. Kudra, T. Energy aspects in drying. Drying Technology **2004**, *22*, 917–932.
22. Menshutina, N.V.; Gordienko, M.G.; Voynovsky, A.A.; Kudra, T. Dynamic analysis of drying energy consumption. Drying Technology **2004**, *22*, 2281–2290.
23. Schmalko, M.E.; Ramallo, L.A.; Morawicki, R.O. A comparison of the diffusion model and the response surface method (RSM) in estimating the drying time of *Ilex paraguariensis*. Latin American Applied Research **1996**, *26*, 215–220.
24. Schmalko, M.E.; Morawicki, R.O.; Ramallo, L.A. Simultaneous determination of specific heat and thermal conductivity using the finite-difference method. Journal of Food Engineering **1997**, *31*, 531–540.
25. Ramallo, L.A.; Pokolenko, J.J.; Balmaceda, G.Z.; Schmalko, M.E. Moisture diffusivity, shrinkage, and apparent density variation during drying of leaves at high temperatures. International Journal of Food Properties **2001**, *4*, 163–170.