

MODELING HEAT AND MASS TRANSFER IN THE HEAT TREATMENT STEP OF YERBA MATÉ PROCESSING

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Abstract - The aim of this research was to estimate the leaf and twig temperature and moisture content of yerba maté branches (*Ilex paraguariensis* Saint Hilaire) during heat treatment, carried out in a rotary kiln dryer. These variables had to be estimated (modeling the heat and mass transfer) due to the difficulty of experimental measurement in the dryer. For modeling, the equipment was divided into two zones: the flame or heat treatment zone and the drying zone. The model developed fit well with the experimental data when water loss took place only in leaves. In the first zone, leaf temperature increased until it reached 135°C and then it slowly decreased to 88°C at the exit, despite the gas temperature, which varied in this zone from 460°C to 120°C. Twig temperature increased in the two zones from its inlet temperature (25°C) up to 75°C. A model error of about 3% was estimated based on theoretical and experimental data on leaf moisture content.

Keywords: Yerba maté; Heat treatment; Modeling; Heat transfer; Mass transfer.

INTRODUCTION

Materials under study were branches of yerba maté (*Ilex paraguariensis* Saint Hilaire). During processing, several chemical compounds in the branches are modified due to the high heat treatment applied. The processing steps are: 1) heat treatment with burning propane (for a few minutes) to inactivate enzymes that produce the browning of leaves (zapeco); 2) drying, carried out in two steps in a cross flow dryer with air at 80-120°C during 1.5 to 4.5 h; 3) grounding to prepare the material for the next step and 4) seasoning, which is carried out in a natural form (during 9 months at room temperature) or controlled form (in chambers at 60°C during 30-60 days).

Besides temperature, water activity (a_w) is another factor that affects the degradation of chemical compounds. In the first two steps of the process, a

large variation in moisture content and thus in water activity occurs. So, in the blanching step, the leaf moisture content varies from 60% (wet basis) to 16% and after drying it reaches 3% (Schmalko and Alzamora, 2001).

According to the moisture content and temperature levels, important changes in chemical components are expected. Schmalko and Alzamora (2001) found that 91.5% of the chlorophyll is lost during processing and 84.2% of this quantity is degraded in the first step. They reported losses of caffeine of about 30% during processing, 8% corresponding to the first step. In this compound, a_w has a special behavior, since it is a water-soluble compound and evaporation losses decrease when water activity increases. When studying pesticide degradation (dimetoathe) in yerba maté leaves, Schmalko et al. (2002) found that 97% of it is degraded during processing, 25% corresponding to

the heat treatment step and 50% to the drying. Ramallo et al. (1998) determined losses of vitamin C during the industrial process, finding that it was reduced to 79% of the original amount in the heat treatment and drying steps. Paredes et al. (2000) noted modifications of sugars (glucose, fructose and sucrose) in these two steps, finding that a decrease in simple sugars and an increase in sucrose content occurred in the heat treatment step, while during drying, changes were not important. According to these results, it can be concluded that losses of chemical compounds in yerba maté in the first and second process steps are important. To minimize these losses, it is necessary to know the variations in yerba maté temperature and moisture content during the process.

In the present work, variations in the yerba maté temperature and moisture content in the heat treatment step were studied. The heat treatment was carried out in a piece of equipment similar to a rotary dryer with intermittent contact between the material and a flame (in the first step). Because of the difficulty in measuring variations in temperature and moisture content in branches (specially in leaves), these two variables had to be estimated for this equipment using heat and mass transfer balance equations.

The aim of this research was to determine variations in temperature and moisture content in leaves and twigs in yerba maté at the heat treatment step, using heat and mass transfer and balance equations.

MATERIALS AND METHODS

Material

Branches of yerba maté (*Ilex paraguariensis* Saint Hilaire) were used as the test material. They were picked by hand and transported to the factory in open trucks. Then they were placed in a freight yard and taken to the rotary kiln dryer for processing. The material was highly heterogeneous (Coelho et al., 2002). Its main characteristics were (Crotti et al., 2002):

- types: ramified and not ramified;
- mean weight: 10.97 g (limit values: 2.5-30 g);
- weighed mean diameter of twigs: 0.0034 m and
- weighed mean thickness of leaves: 0.00036 m.

Equipment

The equipment used consists of a cylinder that rotates by means of gears at low revolutions.

Branches are fed in at the entrance where propane burns and receive heat by convection and radiation. The burner is 0.38 m in diameter and air enters the equipment around the flame. The flame is about 1 m long. Total length of the equipment is 9.6 m. and its internal diameter is 2.57 m.

The equipment, as schematized in Figure 1, has a series of flights 0.025 m in height and 0.060 m in length, arranged at 60° angles with respect to the dryer axis. Seven groups of flights are arranged uniformly with separations of 1 m between them. Each group has 18 flights around the dryer. The arrangement of flights and dryer rotation make branches move from one end to the other, resulting in a parallel flow.

Mean values of working conditions were obtained from measurements made on seven different days (Schmalko et al., 2003). In this research, a solids flow rate was obtained from the production data and a propane flow rate from its consumption during these days. Outlet air temperature was maintained constant by varying propane flow. The other variables were mean values of measurements taken twice daily during seven days. They are the following:

Inlet Conditions

- branch flow rate: 0.422 kg/s (of dry solids);
- leaf flow rate: 0.282 kg/s (of dry solids);
- twig flow rate: 0.140 kg/s (of dry solids);
- air flow rate: 4.01 kg dry air/s;
- absolute humidity of the air: 0.0156 kg water/kg dry air;
- air and solids temperature: 25°C and
- propane flow rate: 0.0482 kg/s

Outlet Conditions

- absolute humidity of the air: 0.140 kg water/kg dry air and
- air temperature: 120°C

Others

- rotation speed of the drum: 10 rpm;
- mean residence time of the branches: 173.9 s with a standard deviation of 56.1 s and
- insulation material and thickness: glass wool of 0.0254 m

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 1.

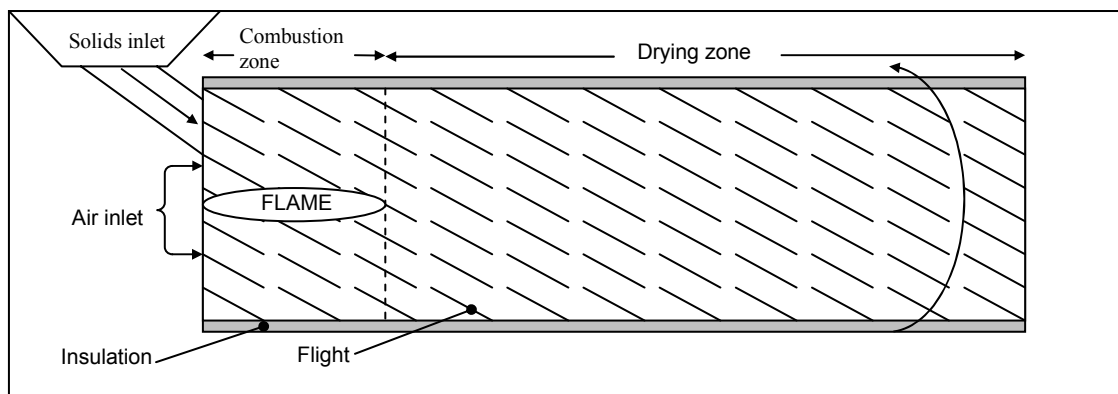


Figure 1: Scheme of the equipment

Table 1: Inlet and outlet moisture contents (on a dry basis) of leaves and twigs measured on seven different days.

Day	Leaves		Twigs	
	Inlet	Outlet	Inlet	Outlet
1	1.4814	0.2112	1.6539	1.3100
2	1.4710	0.1476	1.7747	1.2821
3	1.5806	0.1979	1.7167	1.1777
4	1.5126	0.2066	1.6518	1.1210
5	1.4396	0.1975	1.6867	1.0978
6	1.5058	0.1617	1.6702	1.1119
7	1.4504	0.2118	1.7693	1.3507
Mean value	1.4916	0.1906	1.7033	1.2073

Mathematical Model

Assumptions

To model the dryer, the following assumptions were made:

- 1) the drying of solids takes place only in the gas phase. During the time when solids are lifted by the flights, only moisture redistribution takes place (Kemp and Oakley, 2002);
- 2) there is no temperature gradient in the solids. This is justified by previous research that reported a drop of 1 °C between particle temperature and particle surface temperature (Schmalko and Alzamora, 2005b);
- 3) the twigs are considered composite materials (xylem and bark) and an effective diffusion coefficient is used;
- 4) to estimate equipment heat losses, only heat transfer between the gas and the wall is considered (not that between the solids and the wall);
- 5) heat transfer resistance of the dryer metal walls is negligible (only resistance produced by an insulant is considered);
- 6) burning gases and air form a completely mixed by the end of the heat treatment zone;
- 7) oxygen reacts with propane in a stoichiometric

ratio in the flame;

- 8) a constant product composition exists in the flame, since complete combustion is assumed ;
- 9) gases are considered ideal;
- 10) thermophysical and transport properties of gases are calculated from the individual properties of each one (O₂, N₂, H₂O and CO₂);
- 11) entrance effect on inlet gas flux is considered in calculating the convective heat transfer coefficient;
- 12) variation in surface area due to shrinkage is considered;
- 13) variation in composition of gas phase is considered. It is calculated from mass balances.

According to Schmalko et al. (1996), twigs have capillaries that permit water transfer in an axial direction more easily than in a radial direction (about 200 times). Basilico and Moyne (1986) obtained similar results in wood.

For this reason, two situations were considered in the mathematical model: 1) mass transfer in the twigs takes place in the radial direction and there is no mass transfer between twigs and leaves ($\gamma=1$ in eq.1) and 2) water is transferred from twigs to leaves ($\gamma>1$ in eq.1) in the liquid state and evaporates from them. The water transferred from twigs to leaves in each time step and evaporated in the leaves is $(\gamma-1)*E_1$.

Basic Equations

Heat Transfer

The following differential equations describe the time variation in the leaf, twig and air temperatures (a mixture of inlet air, combustion gases and evaporated water):

leaves:

$$\frac{dT_l}{dt} = \frac{1}{M_{sl}(1+X_l)Cp_l} \left[A_l f_{f-l} \sigma (\varepsilon_l T_g^4 - \alpha_l T_l^4) + A_l h_l (T_g - T_l) - \gamma \lambda E_l \right] \quad (1)$$

twigs:

$$\frac{dT_t}{dt} = \frac{1}{M_{st}(1+X_t)Cp_t} \left[A_t f_{f-t} \sigma (\varepsilon_t T_g^4 - \alpha_t T_t^4) + A_t h_t (T_g - T_t) - \lambda E_t \right] \quad (2)$$

air:

$$\frac{dT_a}{dt} = \frac{1}{M_{sa}(1+X_a)Cp_a} \left[\delta A_f \sigma (T_g^4 - T_a^4) + \delta A_f h_a (T_g - T_a) + E_l \lambda_l + E_t \lambda_t - Q_s - Q_w \right] \quad (3)$$

The temperature notation in the gas phase is “ T_a ” when the solids pass through the flame and “ T_g ” under other situations.

Heat gained by the solid phase:

$$Q_s = \frac{S_l \Delta x A_l}{v_s M_{sl}} \left[h_l (T_g - T_l) + \sigma (\varepsilon_g T_g^4 - \alpha_l T_l^4) \right] + \quad (4)$$

$$+ \frac{S_t \Delta x A_t}{v_s M_{st}} \left[h_t (T_g - T_t) + \sigma (\varepsilon_g T_g^4 - \alpha_t T_t^4) \right]$$

Heat lost:

$$Q_w = \Delta x P \left[h_{wi} (T_g - T_{wi}) + \sigma (\varepsilon_{gi} T_{gi}^4 - \alpha_{wi} T_{wi}^4) \right] = 2\pi k_u \Delta x \frac{(T_{wi} - T_{wo})}{\ln(d_{wi}/d_{wo})} \quad (5)$$

$$= \Delta x P \left[h_{wo} (T_\infty - T_{wo}) + \sigma (\varepsilon_{go} T_\infty^4 - \alpha_{wo} T_{wo}^4) \right]$$

To solve these equations, the finite-difference method was used. The equipment was divided into two zones: the flame or heat treatment zone and the drying zone. In the first zone, propane was burned and branches were in intermittent contact with the flame while, in the second zone, conventional drying occurred. In the numerical solution, forty-eight nodes were used (corresponding to the time required for a branch to pass through the gas phase), five of them in the flame zone and the others in the drying zone. Residence time was considered the same in each node and was calculated dividing the residence time in the equipment by the node number. Each node of the flame zone was divided into three sub nodes, above the flame, in the flame and below the flame, with different residence times that depended on the volume occupied by each one (See Figure 2). The falling time calculated by eq. 6 was 0.72s (Kemp and Oakley, 2002).

$$t_c = \sqrt{\frac{2d_d \sin\theta}{g}} \quad (6)$$

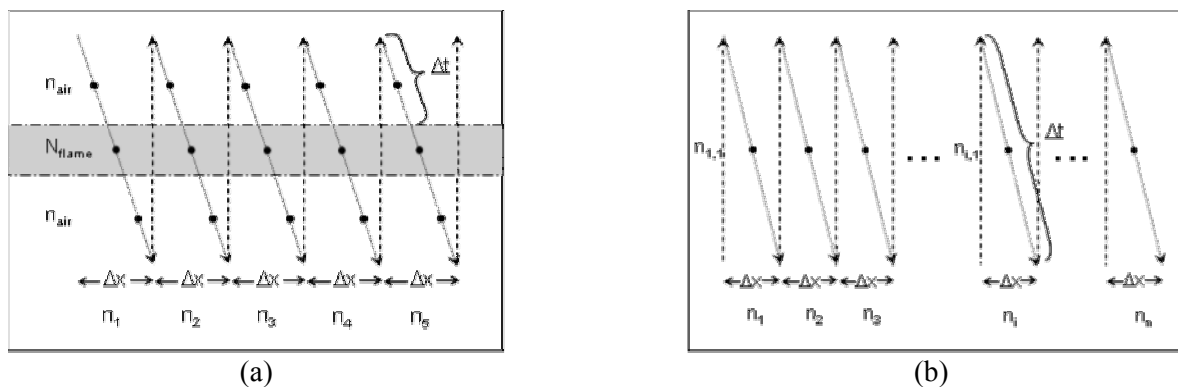


Figure 2: Nodes considered in the model: a) flame zone with its sub zones and b) drying zone

Mass Transfer

Rate of transfer of the water to the air was calculated using the integrated equation of Fick's 2nd law (Suarez et al., 1981). This assumption could be made because the air velocity (>1.5 m/s) was high enough to ensure the internal mass transfer as the main resistance to moisture transfer (Schmalko et al., 1996).

For twigs, the integrated equation for an infinite cylinder with radial transfer was used (Schmalko et al., 1996):

$$\frac{X_t - X_{te}}{X_{t0} - X_{te}} = \sum_{n=1}^{\infty} \frac{4}{\mu_n^2} e^{\left[\frac{-\mu_n^2 D_{eff} t}{R_t^2} \right]} \quad (7)$$

where μ_n are the roots of Bessel functions of first kind and zero order.

For leaves, the integrated equation for an infinite

plane plate was used (Schmalko et al., 1996):

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

Properties

Gas properties and heat and mass transfer coefficients used in the model are shown in Table 2. In order to calculate the convective heat transfer coefficient, the mean composition of the gas was used. In the first zone, the first and third nodes were considered as pure air and the second zone as burning propane at a higher velocity. When the convective heat transfer coefficient of the leaves was estimated, the flux was assumed perpendicular half of the time and parallel the other half.

Table 2: Gas properties and coefficients used in the model

Parameters		References	
$k_m = \frac{\sum_{i=1}^n y_i k_i}{\sum_{j=1}^n y_j B_{ij}}$	$S_i = 1.5 T_{bi}$	$S_{ij} = S_{ji} = (S_i S_j)^{0.5}$	Perry and Green, 1997, p. 2.368
$B_{ij} = 0.25 \left\{ 1 + \left[\frac{\mu_i}{\mu_j} \left(\frac{M_j}{M_i} \right)^{0.75} \left(\frac{T + S_i}{T + S_j} \right) \right]^{0.5} \right\}^2 \left(\frac{T + S_{ij}}{T + S_i} \right)$			Perry and Green, 1997, p. 2.363
$\mu_m = \sum_{i=1}^n \frac{\mu_i}{\left[1 + \sum_{j=1}^n \left(Z_{ij} \frac{y_j}{y_i} \right) \right]}$	$Z_{ij} = \frac{\left[1 + \left(\frac{\mu_i}{\mu_j} \right)^{0.5} \left(\frac{M_j}{M_i} \right)^{0.25} \right]^2}{\sqrt{8} \left(1 + \frac{M_i}{M_j} \right)^{0.5}}$		Perry and Green, 1997, p. 2.363
$C_{p_a} = \sum y C_{p_i}$			Perry and Green, 1997, p. 2.347
$h_{wo} = 0.11 \left(\frac{k_o}{d_o} \right) (0.5 Re_{\omega}^2 + Gr_D Pr)^{0.35}$			Kreith and Bohn, 1997, p. 341
$h_{wi} = 0.023 \left(\frac{k_i}{d_H} \right) Re_{dh}^{0.8} Pr^{0.4} \left(\frac{A_{fa}}{A_{fc}} \right)^{0.1} \left(\frac{A_n}{A_A} \right)^{0.5} (\sec(\beta))^3$			Kreith and Bohn, 1997, p. 418
$h_l = 0.648 \left(\frac{k_g}{L_l} \right) Re_L^{0.5} Pr^{1/3}$	$h_l = 0.205 \left(\frac{k_g}{L_l} \right) Re_L^{0.588} Pr^{1/3}$		Perry and Green, 1997, p. 5.15-5.16
(Parallel flow)	(Perpendicular flow)		
$h_t = 0.51 \left(\frac{k_g}{d_t} \right) Re_d^{0.5} Pr^{0.37}$			Kreith and Bohn, 1997, p. 455
The overall hemispheric emissivity (ϵ) and absorptivity (α) used to calculate radiant heat transfer between surfaces and gases were calculated using the method proposed by Perry and Green (1997, p. 5.33 – 5.34)			

Solids properties and coefficients used in the model are shown in Table 3. Leaf properties were obtained from previous research (Ramallo et al., 2001). The diffusion coefficient of water in the leaves was estimated at between 100 and 130°C. To estimate the diffusion coefficient of the water, the twigs were considered as a composite material (xylem and bark) (Schmalko and Alzamora 2005b).

Experiments were carried out between 70 and 130°C, but in this research, only equations fitted between 70 and 100°C were used. For each material, a different dependence on moisture content and temperature was found (Table 3). Minor errors were found when an effective diffusion coefficient was used; mean percentual error was about 12%, but these errors were lower for a high moisture content (< 3%).

Table 3: Solids properties and coefficients used in the model

Parameters	References
$C_{p_l} = 1.539 \cdot 10^3 + 2.72 \cdot 10^3 \frac{X_l}{(1 + X_l)}$	Schmalko et al., 1997
$C_{p_t} = 1.79 \cdot 10^3 + 2.36 \cdot 10^3 \frac{X_t}{(1 + X_t)}$	Schmalko et al., 1997
$k_l = 0.142 + 0.0051 \frac{X_l}{(1 + X_l)}$	Schmalko et al., 1997
$\lambda = 7020 - 803 \ln(T)$	Perry and Green, 1997
$\rho_l = 560 + 187X_l$ $\rho_t = 701 + 730X_t$	Ramallo et al., 2001 Schmalko and Alzamora, 2005a
$L_l = 2.6 \cdot 10^{-4} + 6.34 \cdot 10^{-5} X_l$	Ramallo et al., 2001
$s_t = \frac{0.613 + 0.192X_t}{0.613 + 0.192X_{t0}}$	Schmalko and Alzamora, 2005a
$D_l = 6.64 \cdot 10^{-6} (1 + X_l) e^{\left[\frac{-3733}{T_l} \right]}$	Ramallo et al., 2001
$D_{lx} = 1.24 \cdot 10^{-7} (1 + 0.75X_t) e^{\frac{-2270}{T_t}} e^{412R_x}$ $D_{tb} = 9.95 \cdot 10^{-5} (1 + 0.28X_t) e^{\frac{-5968}{T_t}} e^{936R_B}$ $D_{ef} = \frac{1}{\left(\frac{d_B - d_x}{d_B} \right) \frac{1}{D_B} + \frac{1}{mD_x}}$ m= slope of the equilibrium line between bark and xylem = 1.61	Schmalko and Alzamora, 2005b

The Flame

To estimate flame temperature, heat balance calculations were carried out at many points along the length of the dryer, resulting in temperatures varying between 1720 and 1820 °C (below the adiabatic flame temperature). In the flame zone, inlet air and burning gases cannot be considered a homogeneous mixture due to the difference in velocity between them (burning gases have higher velocities). Because of this, the flame does not completely mix with air and the division of the node into three sub nodes must be considered.

RESULTS AND DISCUSSION

Model 1

The model developed was applied assuming that there was no mass transfer between twigs and leaves ($\gamma=1$ in eq.1). Theoretical and experimental results on twig and leaf moisture contents and air temperature and humidity at the exit were compared. They were not in good agreement. In the theoretical results the leaf moisture content was lower, the twigs practically did not lose water and their temperature was always higher, air humidity was lower and the

temperature was higher.

These results suggested the need to propose a second model to take into consideration water transfer from twigs to leaves.

Model 2

In the second model, water transfer (in liquid state) from twigs to leaves was considered. All water transferred to the leaves was evaporated from them, and “ γ ” factor of eq. 1 was equal to 1.11. This value was calculated considering the difference between experimental and predicted (with model 1) twig and

leaf water contents. This means that the 11% of additional water coming from the twigs evaporated from the leaves. After each time step leaf and twig moisture contents were corrected to take into account this transfer. It should be mentioned that the leaf heat and mass transfer area was larger than that of the twigs and this produced a higher drying rate, creating a difference in moisture content between them, thus producing water transfer. With these assumptions, agreement between theoretical and experimental data is good. The mean percentual error between experimental and predicted moisture contents is given in Table 4.

Table 4: Outlet experimental and predicted moisture contents (on a dry basis) of leaves and twigs measured on seven different days.

Day	Leaves			Twigs		
	Experimental	Predicted	% Error	Experimental	Predicted	% Error
1	0.2112	0.1665	21.1	1.3100	1.2376	5.5
2	0.1476	0.1589	7.7	1.2821	1.3573	5.9
3	0.1979	0.2262	14.3	1.1777	1.2870	9.3
4	0.2066	0.1849	10.5	1.1210	1.2315	9.9
5	0.1975	0.1424	27.9	1.0978	1.2745	16.2
6	0.1617	0.1806	11.7	1.1119	1.2504	12.5
7	0.2118	0.1486	30.0	1.3507	1.3621	0.8
Mean value	0.1906	0.1674	12.2	1.2073	1.2775	5.8

Temperature

Fig. 3 shows variations in leaf, twig and air temperatures in the equipment for experiment 1. It can be seen that the calculated air temperature increased quickly until $x/L_D = 0.1$ (up to 460°C), corresponding to the end of the flame. From $x/L_D = 0.1$ to $x/L_D = 1$ the temperature decreased (similar to the temperature in other rotary dryers) until reaching 120°C at the equipment exit.

The twigs were heated uniformly heating (from 25°C to 75°C). This usually occurs in solid materials dried in rotary dryers without a constant drying period

(Vega et al., 2000; Ghoshdastidar et al., 2002).

However, the leaves behaved differently. In the first zone (until $x/L_D = 0.1$), they received heat by radiation and convection, and due to the high specific transfer area, their temperature increased up to 135°C (in approximately 17 s). In the second zone, the leaf temperature decreased slightly, because the heat gain was less than that necessary to evaporate water. The evaporation rate was high because leaf temperature was very high. The exit leaf temperature was about 88°C . These high temperatures produced physical damage to the leaves, as can be observed at the equipment exit (for example, leaf epidermis cracking).

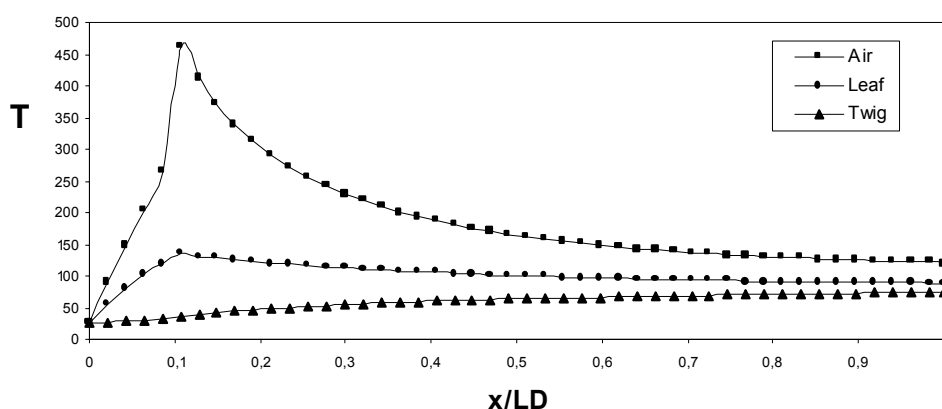


Figure 3: Variation in temperature along the length of the equipment (dimensionless distance).

Moisture Content

Fig. 4 shows the variation in leaf and twig moisture contents along the length of the equipment in experiment 1. In the first zone, losses of leaf moisture content had a special behavior due to the quick rise in temperature. In the second zone (the

drying zone), the decrease in leaf moisture content had a logarithmic form assumed by Fick's model. This decrease was slower than those found by other authors (Kemp and Oakley, 1997; Vega et al., 2000; Ghoshdastidar et al., 2002). This was probably due to the reduction in leaf temperature and to the water gained from the twig and evaporated from the leaves.

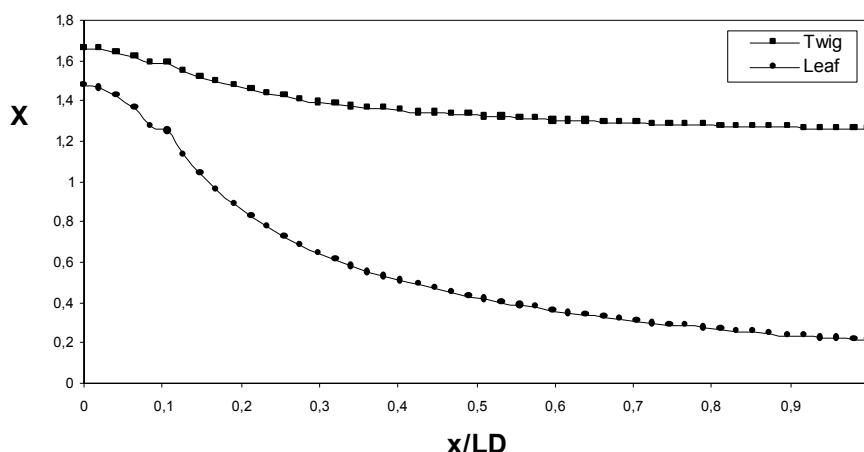


Figure 4: Variation in leaf and twig moisture contents along the length of the equipment (dimensionless distance)

CONCLUSIONS

A model of heat and mass transfer of branches of yerba maté in a rotary kiln dryer was developed. A low error was found when water evaporation taking place mainly in the leaves was taken into account.

In the first zone, where the material was in contact with burning propane, a high increase in leaf temperature occurred (reaching 135°C) in contrast to a slow increase in twig temperature. This difference was due to the large difference in the heat and mass transfer area between leaves and twigs.

In the second zone, the leaf temperature decreased slowly because of its high initial temperature and drying rate, which is considered unusual in a rotary dryer. Temperature of the twigs increased as expected.

Variations in leaf moisture content had an unusual profile in the first zone due to their high increase in temperature and a logarithmic profile in the second zone.

NOMENCLATURE

A Mean surface transfer area (m²)
 A_{fa}, A_{fc} Transfer areas used to (-)

A_n, A_A estimate heat transfer coefficient in twigs (free flow area, flow area between flights, heat transfer area without taking flights and actual area of heat transfer into account)
 a_w Water activity (-)
 B_{ij} Coefficients used to estimate thermal conductivity (-)
 C_p Specific heat capacity (J/kg K)
 d Twig diameter (m)
 D Water diffusion coefficient (m²/s)
 d_d Internal diameter of the equipment (-)
 d_H Hydraulic diameter (m)
 E Water evaporation rate (kg/s)
 f View factor (-)
 Gr Grasshoff number (-)
 h Convective heat transfer coefficient (J/m² K)
 k Thermal conductivity (J/m K)
 L Leaf thickness (m)
 L_D Equipment length (m)
 M Molecular weight
 M_s Dry mass (kg)

n_i	Number node	
P	Internal perimeter of the dryer	(m)
Pr	Prandlt number	(-)
Q	Heat flux	(J/s)
R	Twig radius	(m)
Re	Reynolds number. To estimate Reynolds number, leaf length and twig diameter were used as characteristic length	(-)
S_{ij}	Coefficients used to estimate thermal conductivity	(-)
S	Shrinkage coefficient	(-)
t	Time,	s
t_c	Falling time of branches,	(-)
T	Temperature	(K)
v_s	Mean rate of solids in the dryer	(m/s)
x	Distance from the end of the inlet	(m)
X	Moisture content	(kg water/kg dry solid)
y	Molar fraction of gases	(-)
Z	Coefficient used to estimate viscosity	(-)

Greek Letters

α	Overall hemispheric absorptivity	(-)
β	Flight angle in respect to dryer axis	(-)
Δx	Node length	(m)
δ	Coefficient zone	(=1 in the flame zone and =0 in the drying zone)
γ	Coefficient taking into account water evaporation in leaves coming from twigs	(-)
ε	Overall hemispheric emissivity	
λ	Evaporation latent heat	(J/kg)
ρ	Density	(kg/m ³)
σ	Stefan-Boltzman constant	(J/m ² K ⁴)
θ	Angle where solids fall from flights. A mean value of 2π is considered	(-)
μ	Gas viscosity	(kg/m s)

Subscripts

a	Air	(-)
B	Bark	(-)
e	Equilibrium	(-)
ef	Effective property of the twig	(-)
f	Flame	(-)
g	Gases	(-)
l	Leaf	(-)
m	Mean	(-)
o	External	(-)
s	Surface	(-)
t	Twig	(-)
u	Insulant	(-)
wi	Internal wall	(-)
wo	Outer wall	(-)
X	Xylem	(-)
0	Initial	(-)
∞	External air	(-)

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