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Modeling and minimizing process time of combined convective and vacuum drying of mushrooms and parsley

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ABSTRACT

The aim of this work was to obtain a technological and economic alternative for mushroom and parsley dehydration combining convective and vacuum drying. Depending of product, this combination of technologies allows minimization of total drying time and avoids negative effects on quality of thermo-sensitive products during drying. Experimental drying curves were determined in a cross-flow convective dryer and in a cabinet vacuum dryer at 35, 45 and 55 °C. The most appropriate theoretical models were obtained and applied for combined processes in order to minimize the overall drying time and avoid final product damage. For parsley at the highest temperature (45 °C), reductions of 63% and 16% in drying time were observed with the combined drying process compared to the sole convective and sole vacuum drying, respectively. This reduction in process time was obtained when dryer change was done at the intermediate moisture condition that determines the highest drying rate during the whole combined process of convective and vacuum drying. For mushrooms, convective drying throughout the process, at the highest temperature (55 °C) compatible with product visual quality, minimized drying time.

1. Introduction

New trends in the development and improvement of processes and products in the dehydrated food area lead to the combination of different conventional and non-conventional drying technologies. The objective of this trend is to accomplish a drying strategy that contemplates changes in product as its moisture decreases, by adapting to its increasing thermo-sensitivity and thus avoiding main damages in final product with an efficient and cost-effective process appropriate to the product value in the market.

Depending on the product, one or more characteristics (aroma, taste, texture, integrity, etc.) will define acceptance by the consumers as well as the value of the product. Conventional convective drying technologies produce negative effects in many natural thermo-sensitive products, even for low temperatures when the moisture of the product is low (Mujumdar, 1995). In parsley, the main problems are aroma degradation and yellowing, in comparison to the fresh green product. For mushrooms, the main problems are changes of color and texture (Askari et al., 2009; Kotwaliwale et al., 2007). Freeze-drying, which has been developed as a dehydration process for high quality products, proves to be economically viable only for very high value products (Ratti, 2001). For these reasons, neither convective drying nor freeze-drying constitute adequate technological solutions for the industrial production of many of commercially important dehydrated products. Numerous studies relate the final quality of dehydrated products with drying process conditions (Gothandapani et al., 1997; Kotwaliwale et al., 2007; Markowski and Bialobrzewski, 1998; Martínez-Soto et al., 2001; Xanthopoulos et al., 2007). These studies show the sensitivity of mushrooms to temperature. High air dry temperatures ($T > 60$ °C) cause darkening in color, hardening and decrease in rehydration ability as showed by Kotwaliwale et al. (2007). Although numerous modeling and experimental studies have been carried out to investigate drying of mushrooms, few works about heat and mass transfer phenomena models are reported (da Silva et al., 2009; Efremov, 2002; Jaya and Das, 2003; Reyes et al., 2002). There are also few studies on parsley drying technologies and quality (Kavav Akpinar et al., 2006; Doymaz et al., 2006). For the case of parsley drying, it is known that temperatures in excess of 60 °C cause a significant loss of herb volatile oils. Drying of parsley at 40 °C with a large volume of air moving through the material, reduces the loss of oils before color loss, maintaining flavor in the dried flakes, but long drying time is required and the quality of the dehydrated product is usually not good. In recent years some studies about combined drying processes were published, (Contreras et al., 2008; Cui et al., 2003; Figiel, 2009; Giri and Prasad, 2007a,b; Rodríguez et al., 2005; Sharma and Prasad, 2001; Walde et al., 2006). Most of them develop empirical models, semi empirical models or surface response methodology for the description of the process (Madamba and Libbon, 2001).

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Nomenclature

α, β	models constant
D_e	effective diffusivity (m^2/s)
D_0	initial effective diffusivity (m^2/s)
db	dry basis
%e	absolute average error percentage
Fo	Fourier number ($D_e t/L^2$)
%HR	relative humidity percentage
L	half thickness of slab (m)
n	number of experimental values
P	pressure (in Hg)
t	process time (min)
t_0	initial time of drying process (min)
$t_{C,A}$	convective drying time to achieve intermediate moisture (min)
$t_{C,F}$	convective drying time to achieve final moisture (min)
$t_{V,A}$	vacuum drying time (min)
$t_{V,F}$	vacuum drying time to achieve intermediate moisture (min)
T	temperature (°C)
X	moisture content (kg water/kg dry matter)
$\overline{X}$	average moisture content (kg water/kg dry matter)
X_A	intermediate moisture (kg water/kg dry matter)
X_{calc}	theoretical moisture calculated, Eqs. (7)–(9) (kg water/kg dry matter)
X_e	equilibrium moisture content (kg water/kg dry matter)
X_{exp}	experimental moisture (kg water/kg dry matter)
X_F	final moisture (kg water/kg dry matter)
X_0	initial moisture content (kg water/kg dry matter)
wb	wet basis
z	spatial coordinate (m)

The objectives of this work were to study, model and minimize the process time for a combination of convective and vacuum drying for mushrooms and parsley dehydration. The hypothesis is that this combination can be an adequate technological solution for reducing dehydration process time for many thermo-sensitive natural products. The predictive models formulated can be used as a tool for determining process time, for process control or for evaluation of the effect of modifications in the process variables.

2. Materials and methods

2.1. Drying experiments

Pleurotus mushrooms and Italian parsley were selected because of their high market value as dehydrated products.

A convective cross-flow air dryer and a vacuum cabinet dryer were used as experimental systems for determination of parsley and mushrooms drying curves Samples of approximately 200 g of fresh parsley and mushrooms were dried from fresh product moisture (92.5% (wb) for mushrooms and 85% (wb) for parsley) to a final moisture of 5–7% (wb).

For convective air-drying experiences, a cross-flow convective dryer instrumented with controls for air velocity and temperatures, was used. Sensors of air temperature and relative humidity were installed and connected to data-logger for recording experimental data of air conditions during drying (Vaisala, mod HMI 38, Finland). All tests were carried out with an air velocity of 1 m/s for three levels of temperatures (35, 45 or 55 °C). Samples were weighted periodically during the drying process and loss of weigh as function of time was computed.

Vacuum drying experiments were done in a vacuum cabinet dryer, instrumented with temperature and pressure controls, and a continuous weighting system with a load cell inside the cabinet for data transmission (weight and time) to a remote balance display and a computer for data storage. Ambient conditions (T, %HR) inside and outside the vacuum chamber were registered. Experiences of vacuum drying were done for three different temperatures (35, 45 and 55 °C) and at an operating pressure of 28 in Hg.

For all samples assayed, moisture content of initial and dehydrated product was determined gravimetric method at 105 °C (AOAC, 1990).

Data obtained from these experiments were fitted to models of convective and vacuum drying in the whole range of products moistures (from X_0 to X_F).

In addition to experiments of drying in each individual dryer, experiments combining both drying processes were carried out, beginning with the fresh product in the convective dryer and ending with the vacuum dryer. In this experience, same conditions of temperature and air velocity for convective drying as well as same conditions in temperature and pressure in the vacuum dryer were set. The intermediate moisture for changing from convective dryer to vacuum dryer was determined from drying rate curves and models obtained for each drying technology, as discussed in Section 2.3.

At the end of each experience, dehydrated products' visual appearance (yellowing, darkening, and shrinking) was evaluated qualitatively.

2.2. Mathematical modeling

Phenomenological models with diffusive control of drying processes, for both convective and vacuum dehydration were formulated. In structured foods, the common approach to modeling mass transfer is to use an effective diffusion coefficient defined by the Fick's second law where the diffusion coefficient may be dependent on the product moisture content. This effective diffusivity usually considers other simultaneous mechanisms of transport as capillarity flow of liquid, vapor diffusion, hydrodynamic flow of liquid and vapor due to pressure gradients and condensation–evaporation in a receding front. Others factor as porosity and tortuosity are also lumped in this effective coefficient. In this way, we used the concept of effective diffusivity, D_e, and Fick's second law to describe moisture transport during drying of parsley and mushrooms:

$$\frac{\partial X}{\partial t} = \frac{\partial}{\partial z}\left(D_e \frac{\partial X}{\partial z}\right) \tag{1}$$

In order to solve Eq. (1), geometry, initial conditions and boundary conditions must be established for the considered drying processes. In many cases, the shape of the solid to be dried is very complex and cannot be assimilated to any simple geometry, as occurs with mushrooms or parsley leaves in a cross-flow air convective dryer or in a cabinet vacuum dryer. The simplest assumption is to assimilate the system geometry to an infinite plane of equivalent thickness $2L$, and the differential equation solution for average moisture will be expressed as a function of the Fourier number for mass ($Fo = D_e t/L^2$) where (D_e/L^2) is a parameter of the system that will be determined.

Two possibilities were considered for the dependency of diffusivity with moisture content of the solid: firstly, the effective diffusivity remains approximately constant during the process, being:

$$D_e = D_0 \quad \forall t \geqslant 0 \tag{2}$$

and secondly, diffusivity varies with moisture content and structural changes that occur in the solid during dehydration in the falling rate period. This variation can be considered as a functional relationship between the effective diffusivity and the Fourier number (Alvarez and Legues, 1986):

$$D_e = D_0(1+\mathrm{Fo})^{\beta-1} \quad \forall t \geqslant 0 \tag{3}$$

A homogenous and isotropic behavior of the product and a uniform distribution of moisture in the sample at initial time were assumed. This initial condition is:

$$X = X_0 \quad -L \leqslant z \leqslant L, \quad t = 0 \tag{4}$$

Two different hypotheses were considered for the boundary conditions of the system: on one hand, the interface moisture content remains constant in equilibrium condition during the process:

$$X = X_e \quad z = \pm L, \quad t \geqslant 0 \tag{5}$$

and on the other hand, the interface moisture content changes rapidly but not instantaneously and it was assumed that the interface condition varies exponentially with drying time, as moisture in the solid decreases:

$$\frac{X - X_e}{X_0 - X_e} = e^{\left(-\frac{\alpha D_e}{L^2} t\right)} \quad z = \pm L, \quad t \geqslant 0 \tag{6}$$

Furthermore, the diffusion coefficient of water in the solid is a transport property that usually depends on the temperature of the product.

Integrating Eq. (1) for the different hypotheses about diffusivity dependence and interface conditions, a set of solutions for the variation of moisture content in space and time were obtained. The average moisture in the whole solid, as a function of the process time, was obtained by integrating with respect to space variable, *z*, between limits $-L$ and $+L$, resulting in the following equations (Crank, 1998):

Case 1: Constant surface concentration and constant effective diffusivity.

$$\frac{\overline{X} - X_e}{X_0 - X_e} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{\exp\left(\frac{-(2n+1)^2 \pi^2 D_e t}{4L^2}\right)}{(2n+1)^2} \tag{7}$$

Eq. (7) results from solving Eq. (1) with constant diffusivity, Eq. (2), and initial and boundary conditions given by Eq. (4) and Eq. (5) and then integrating for average moisture in the whole solid product.

Case 2: Constant surface concentration and variable effective diffusivity.

$$\frac{\overline{X} - X_e}{X_0 - X_e} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \times \exp\left(\frac{-(2n+1)^2 \pi^2}{4\beta}\left(\left(1 + \frac{D_e t}{L^2}\right)^{\beta} - 1\right)\right) \tag{8}$$

Eq. (8), results from solving Eq. (1) with variable diffusivity, Eq. (3), and initial and boundary conditions given by Eq. (4) and Eq. (5) and then integrating for average moisture in the whole solid product.

Case 3: Variable surface concentration and constant effective diffusivity.

$$\frac{\overline{X} - X_e}{X_0 - X_e} = e^{\left(-\frac{\alpha D_e}{L^2} t\right)} \left(\frac{\tan \alpha}{\alpha}\right)^{1/2} + \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{\exp\left(\frac{-(2n+1)^2 \pi^2 D_e t}{4L^2}\right)}{(2n+1)^2 \left[1 - (2n+1)^2 \frac{\pi^2}{4\alpha}\right]} \tag{9}$$

Eq. (9), results from solving Eq. (1) with constant diffusivity, Eq. (2), and initial and boundary conditions given by Eq. (4) and Eq. (6) and then integrating for average moisture in the whole solid product.

Case 1 represents the simplest type of diffusion process and the analytical solution given by Eq. (7) is proposed very frequently for modeling convective drying. Case 2 uses a variable diffusion coefficient in time, allowing the consideration of the effect of changes in moisture and structure that occur in the solid during drying, affecting diffusivity value. Case 3, which considers a variable interface condition, may be a good approach considering that surface concentration changes rapidly but equilibrium conditions are not established instantaneously at initial time.

The models representing drying curves, given by Eqs. (7)–(9) were tested for sole convective drying, sole vacuum drying and a combination of both technologies for the whole dehydration process for different operating conditions, in mushrooms and parsley dehydration.

Computational programs for non-linear multiparametric regression were developed using PC-Matlab 6.0 software. Fitting was made using a computational program that minimizes the absolute average error percentage between experimental and theoretical values. The numerical method used was Simplex, which employs the Nealder–Mead algorithm for non-linear optimization calculus, determining the resulting values of the parameters that optimize the fitting of each theoretical model and the corresponding experimental data ($\overline{X}$, t).

The absolute average error percentage between theoretical moisture and experimental value were calculated as:

$$\%e = \frac{100}{n} \sqrt{\sum (X_{calc}^2 - X_{exp}^2)} \tag{10}$$

Comparison between the absolute average error percentage calculated by Eq. (10) for each case (two products, two processes, three levels of temperature and three theoretical models) allowed the determination of the best model for the description of drying kinetics for convective and vacuum drying.

2.3. Determination of the best combination of both processes

The combined process can be described by the combination of the convective and vacuum drying individual kinetics models. Using individual models, it is possible to determine the intermediate moisture (X_A) of each product at which the change of dryer should be carried out. This intermediate moisture was determined as the moisture value at which the relative drying rate of both processes was reversed. Changing of drying technology at this moisture, results in minimizing the overall time of the combined drying process. These intermediate moisture value that depends on temperature, vacuum pressure, initial moisture content and product, was selected in order to maintain the highest drying rate during the whole combined process of convective and vacuum drying (from X_0 to X_F).

Figs. 1 and 2 represent the procedure to determine the value of intermediate moisture (X_A) and minimum time for the whole combined process.

From the drying rate curves (Fig. 1) at the same temperature for both processes, the intersection point (X_A/X_0) corresponding to the same drying rates in both individual convective and vacuum drying processes is determined. A mathematical analysis of drying rate curves functions shows that for dimensionless moisture values higher than X_A/X_0, convective drying rate is higher than vacuum drying. For dimensionless moisture values lower than X_A/X_0, vacuum drying is faster than convective drying. In this way, the faster process is achieved when process starts with convective drying and changes to vacuum drying at the intermediate moisture (X_A). This procedure determines the minimum time of combined process.

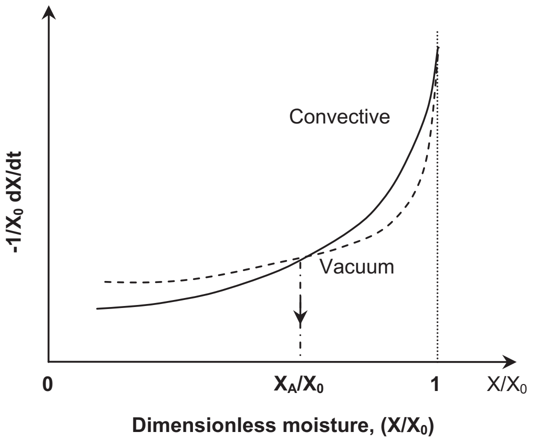

Fig. 1. Scheme to determine the intermediate moisture for change of dryer.

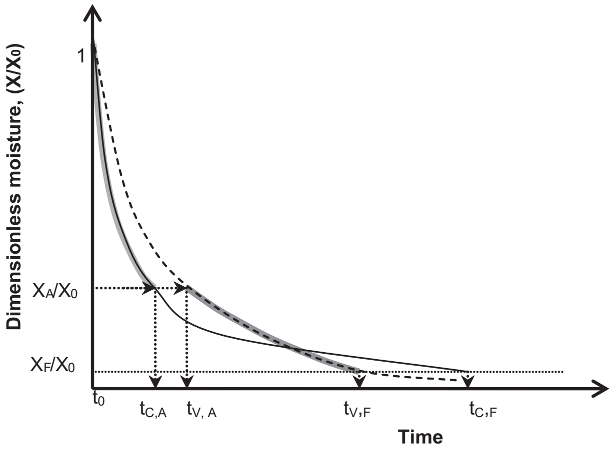

Fig. 2. Scheme to determine the minimum time of combined process. Convective (—) and vacuum (- - - -) drying curves, (▬) first and second stage of combined process.

Convective process time ($t_{C,A} - t_0$) is required for reduction of moisture from the initial value, X_0 to intermediate moisture, X_A. From convective drying curve, abscise value of point (X_A/X_0, $t_{C,A}$) determine $t_{C,A}$ (Fig. 2). In this moment the change of dryer is done. The vacuum drying is the second stage of combined drying process, beginning when moisture of product reaches the intermediate value X_A. This process continues until the final moisture of the product (X_F) is reached at final time t_{VF}. From vacuum drying curve, abscise value of time ($t_{V,A}$), corresponding to intermediate moisture value X_A of product can be determined (Fig. 2). Vacuum drying time results to be ($t_{V,F} - t_{V,A}$).

When combination of convective and vacuum drying is performed, the minimum total time required to achieve final moisture of the dehydrated product, can be calculated as:

$$t = (t_{C,A} - t_0) + (t_{V,F} - t_{V,A}) \tag{11}$$

When convective drying is the first stage of the combined process, its initial time is $t_0 = 0$. So the convective drying time results to be equal to $t_{C,A}$, while for vacuum drying the required time is ($t_{V,F} - t_{V,A}$).

For combined process, the overall time required can be calculated from Eq. (11) where values of $t_{C,A}$, $t_{V,A}$, and $t_{V,F}$, are calculated from equations of models for each convective and vacuum process as the abscise of points (X_A, $t_{C,A}$), (X_A, $t_{V,A}$), and (X_F, $t_{V,F}$).

When there is an intersection of drying rate curves, in the range of drying moisture and processes temperature, combined process time (t) results to be lower than required drying time from X_0 to X_F when only one of dryer technologies is used.

When sole convective dryer is applied, time required for dehydration from X_0 to X_F is ($t_{C,F} - t_0$), while in case that only vacuum drying is applied, time required is ($t_{V,F} - t_0$) for the same range of moisture (X_0 to X_F) and temperature.

Initial moisture content of fresh product is normally a high value and convective drying results to be the fast technology in the beginning of the process. As Fig. 2 shows, the saving time resulting of combining convective and vacuum drying can be calculated as:

$$t_{saved} = (t_{V,A} - t_{C,A}) + (t_{C,F} - t_{V,F}) \tag{12}$$

which is a positive number for the case that an intersection of drying rates curves exists at a moisture value in range of moistures and temperature of the processes.

3. Results and discussion

3.1. Kinetics of convective drying, vacuum drying and combined technologies

For each product (parsley and mushrooms) and for each drying process (convective and vacuum) at three different temperatures, drying curves and drying rate curves were determined.

The three different theoretical models proposed were fitted with experimental data for each temperature. The parameters of each model and the absolute average error percentage are listed in Tables 1 and 2 for parsley and mushrooms, respectively.

Table 1
Parameters of different models determined for parsley drying.

		Convective drying			Vacuum drying		
Drying conditions	T (°C)	35	45	55	35	45	55
	P (in Hg)	0	0	0	−28	−28	−28
	X_0 (g_{H_2O}/g_{SS})	7.41	5.67	7.63	6.37	6.19	5.69
Model 1	$D_e/L^2 \times 10^3$ (min^{-1})	1.42	1.63	6.91	0.42	1.01	1.54
	%e (abs, average)	5.8	3.6	3.3	1.7	2.4	7.1
Model 2	$D_e/L^2 \times 10^3$ (min^{-1})	1.87	1.77	6.19	0.20	0.49	0.075
	β	−0.29	0.54	1.62	7.62	7.02	7.18
	%e (abs, average)	1.8	3.3	2.1	7.4	7.7	1.8
Model 3	$D_e/L^2 \times 10^3$ (min^{-1})	–	–	–	2.19	6.19	9.72
	α	∞	∞	∞	0.72	0.59	0.57
	%e (abs, average)	–	–	–	0.3	0.5	0.9
	For $\alpha \to \infty$ ($\alpha > 10$), Model 3 reduce to Model 1						

Table 2
Parameters of different models determined for mushrooms drying.

		Convective drying			Vacuum drying		
Drying conditions	T (°C)	35	45	55	35	45	55
	P (in Hg)	0	0	0	−28	−28	−28
	X_0 (g_{H_2O}/g_{SS})	8.65	11.20	11.31	7.16	15.40	11.27
Model 1	$D_e/L^2 \times 10^3$ (min^{-1})	3.85	6.29	7.19	0.25	0.42	0.78
	%e (abs, average)	4.9	6.1	9.0	2.5	6.7	5.1
Model 2	$D_e/L^2 \times 10^3$ (min^{-1})	3.72	7.36	6.14	0.069	0.12	0.26
	β	1.19	0.33	1.92	21.51	22.73	15.18
	%e (abs, average)	4.9	4.6	8.3	0.4	1.2	1.2
Model 3	$D_e/L^2 \times 10^3$ (min^{-1})	–	–	–	0.63	1.17	1.95
	α	∞	∞	∞	2.23	2.11	2.24
	%e (abs, average)	–	–	–	0.9	2.2	1.3
	For $\alpha \to \infty$ (α > 10), Model 3 reduce to Model 1						

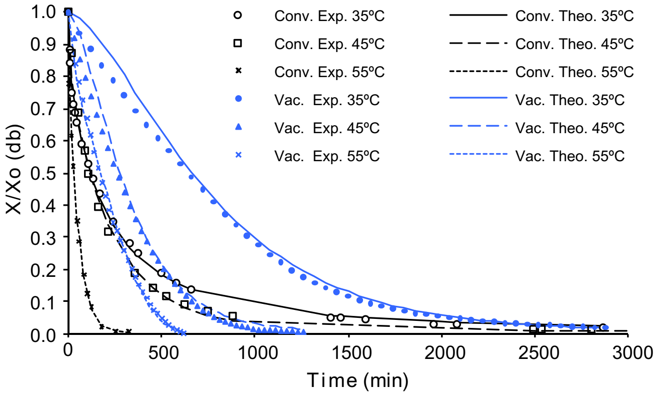

Fig. 3. Experimental data and best theoretical model for convective and vacuum drying of parsley, at different temperatures.

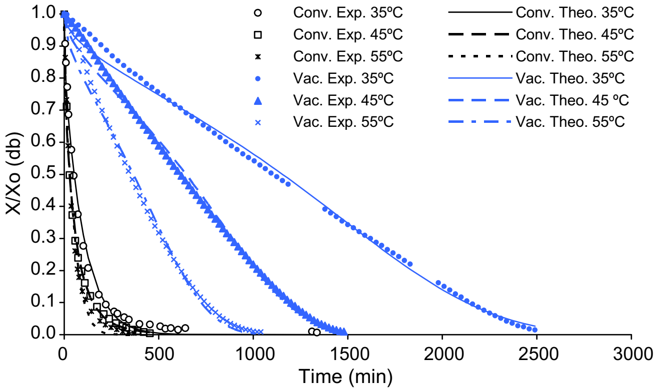

Fig. 4. Experimental data and best theoretical model for convective and vacuum drying of mushrooms, at different temperatures.

Experimental values and the theoretical curves corresponding to the best models for the convective and vacuum drying are shown in Fig. 3 for parsley and in Fig. 4 for mushrooms.

For both parsley and mushrooms and for all temperatures, the best model in predicting the convective drying process was model 2, Eq. (8), obtained for variable diffusion coefficient as function of Fo number and constant surface concentration. For vacuum drying at the same temperatures, model 3, Eq. (9), which considers constant effective diffusivity and exponential variation in time of the surface moisture content, was the best one. Model 1, Eq. (7), the classical diffusion model with constant effective diffusivity and equilibrium as surface condition, was not adequate for the description of any of the process at any temperature assayed.

The models selected for each case can predict the evolution of average moisture in time with a percentage of absolute average error between 0.3% and 8.3%.

The combined dehydration process began with the convective drying and followed by vacuum drying. Combining the individual models determined for each process could represent the experimental kinetics of the combined process.

Figs. 3–6 show that drying rate increases when the process temperature increases in both convective and vacuum drying. For the same temperature, mushrooms convective drying was faster than parsley convective drying. However, parsley vacuum drying was faster than mushrooms vacuum drying. For high moistures, convective drying occurred at higher rates than vacuum drying for both products at all temperatures assayed. When moisture decreased, convective drying rate diminished faster than vacuum drying rate. Both drying temperature (a constant parameter of the processes) and product moisture (which decreases during the process), determine simultaneously the instantaneous drying rate.

Evaluation of main characteristics of dehydrated products, show important yellowing and texture damage for drying temperature over 45 °C for parsley while darkening and shrinking are important for drying temperatures over 55 °C for mushrooms. Visual appraisal showed that the highest temperature assayed that determines highest drying rate for each process without appreciable damage was 45 °C for parsley and 55 °C for mushrooms.

3.2. Combination of processes for minimum overall time

Figs. 5 and 6 show the curves obtained for convective and vacuum drying rates for parsley and mushrooms as function of dimensionless moisture of the product. Intermediate moisture at which relative rates of both processes was reversed is also indicated in these figures. At this intermediate moisture, change of dryer should be done. This situation was very clear in the case of parsley, but not in the case of mushrooms, where the reversion of drying rates did not occur for the range of temperatures studied.

At 55 °C mushrooms convective drying rate is high and its reduction, when low moisture contents in the products is achieved, is not enough for producing a reversion of drying rates in relation with vacuum drying process. Convective drying at this temperature remains at higher rates than vacuum drying for the whole moisture range and sole convective drying of mushrooms at this temperature is the option that minimizes the drying time. Restrictions to this criterion will only be imposed by the maximum drying temperature in order to avoid damage of the product.

Fig. 7 shows the reduction of total time process when combined convective and vacuum drying for parsley is used. Minimum time of the combined process was determined, starting with convective

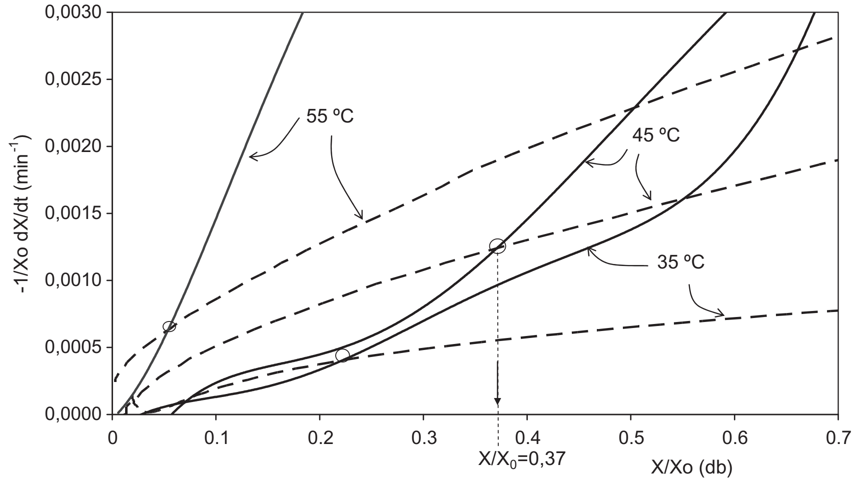

Fig. 5. Convective (—) and vacuum (- - - -) drying rates of parsley as a function of dimensionless moisture of product at different temperatures.

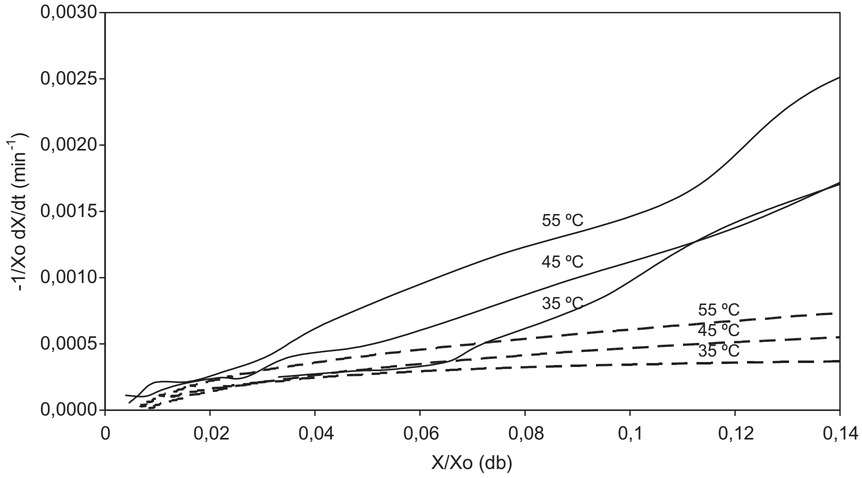

Fig. 6. Convective (—) and vacuum (- - - -) drying rates of mushrooms as a function of dimensionless moisture of product at different temperatures.

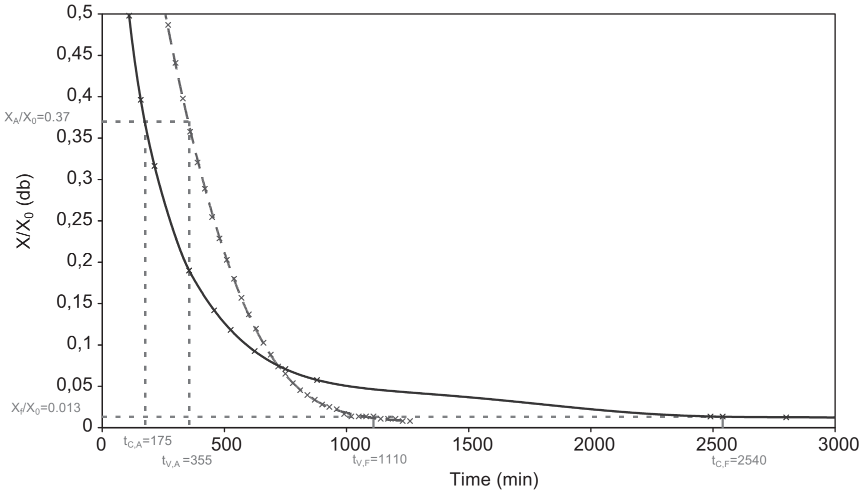

Fig. 7. Determination of minimum drying time of parsley combining processes. Convective (—) and vacuum (- - - -) drying curves of parsley for 45 °C.

drying process and fresh product. It could be seen that when operating at the maximum suitable drying temperature (45 °C), the reversion of drying rates occurred at $(X_A/X_0) = 0.37$, which corresponded to a product moisture of 67% (wb). For lower moisture content, drying should be continued in a vacuum dryer at 45 °C, in order to dry parsley from a moisture content of 67% to the final moisture content (7%) (wb). The minimum time of the process was 930 min. Dehydration of parsley under same conditions lasted 2540 min for sole convective drying and 1110 min for sole vacuum drying. Therefore, the combined process saved 63.4% of process time in relation to using convective drying for the whole process and saved 16.2% of process time in relation to using vacuum drying for the whole process.

Convective drying was the best technology for mushroom dehydration considering process time and visual appearance of product. Minimum process time was 342 min when drying fresh mushroom (X_0 = 92.5% (wb)) in a convective dryer at 55 °C to final moisture content (7%) (wb) while in a vacuum dryer for the same temperature and moistures, process time was 1050 min.

4. Conclusions

For vacuum and convective drying during the falling rate period, a set of simple diffusive models were developed assuming that diffusion coefficient of water is constant or alternatively considering that water diffusivity is variable with drying time or Fourier number ($\mathrm{Fo} = D_e t/L^2$). Two different boundary conditions were considered: a constant equilibrium concentration at the interface for the overall process and a variable surface concentration depending on time (Fourier number). This types of models based on Fick's law, were successful in predicting convective and vacuum drying process of parsley and mushroom. Model 2, obtained for variable diffusion coefficient as function of Fo number resulted in the best option for modeling convective drying for parsley and mushrooms for the overall range of temperatures assayed. On the other hand, Model 3 considering constant effective diffusivity and exponential variation in time of the surface moisture content was the best option for modeling vacuum drying for parsley and mushrooms in the overall range of temperatures assayed. These models were successfully used in determining the intermediate moisture for dryer change in order to minimize and estimate the overall time of the combined process.

The highest temperature assayed in this study, at which drying could be performed without appreciable visual damage was 45 °C for parsley and 55 °C for mushrooms. For parsley, an important reduction of process time was achieved when convective and vacuum drying at the maximum suitable drying temperature (45 °C) was combined. For mushrooms, when drying was performed at the maximum temperature the most appropriate technology was the dehydration process in a convective dryer, because the reversion of the processes' rates did not occur for this product and temperature.

Future studies for other products should be carried out in order to prove greater utility of the combined convective and vacuum drying process.

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