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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.