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Mushrooms dehydration in a hybrid-solar dryer, using a phase change material

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ABSTRACT

Mushrooms were dehydrated in a hybrid solar dryer provided with a solar panel of a total exposed surface of 10 m^2, electric resistances and paraffin wax as a phase change material. Mushrooms were cut in 8 mm or 12 mm slices. At the outlet of the drying chamber the air was recycled (70% or 80%) and the air temperature was adjusted to 60 °C. At the outlet of the solar panel the air temperature rose up to 30 °C above the ambient temperature, depending on solar radiation level.

The effective diffusivity, estimated by the Simplified Constant Diffusivity Model, considering or not shrinkage, fluctuated between $2.5 \cdot 10^{-10}$ m^2/s and $8.4 \cdot 10^{-10}$ m^2/s with R^2 higher than 0.99, agreeing with values reported in literature. The empirical Page's model resulted in a better adjustment, with R^2 above 0.998.

In all runs the dehydrated mushrooms showed a notorious darkening and shrinkage. Rehydration assays at 30 °C showed that in less than 30 min rehydrated mushrooms reached a moisture content of 1.91 (dry basis). Rehydrated mushrooms had a higher hardness compared with fresh mushrooms. The Simplified Constant Diffusivity Model and the Peleg's model adjusted to the rehydration data with RMSE values below 0.080.

Thermal efficiency fluctuated between 22% and 62%, while the efficiency of the accumulator panel varied between 10% and 21%. The accumulator allowed reducing the electric energy input.

1. Introduction

The energy necessary for drying usually comes from fossil fuels, whose prices are continuously rising and their negative environmental impact due to CO_2 emissions is increasingly challenged. The use of renewable non conventional energy has allowed reducing the use of fossil fuels [1–4]. Additionally, the solar energy is a promising energy source, despite its daily and seasonal fluctuations that represent a severe drawback. This makes it necessary to use additional energy sources (biomass, hydrocarbons or electric energy) and/or solar energy accumulators with phase change materials (PCM), that allow the operation of solar dryers during the low or null irradiation periods [7,8].

PCM are materials that accumulate energy when changing from solid to liquid state (melting heat), and turns it over when changing from liquid to solid state (solidification heat). Phase change heat exhibits a high heat density and a minimum temperature variation during fusion and solidification periods. PCM are classified in organic and inorganic. Organic PCM have the advantage of keeping their properties independently of how many times they melt or solidify [9,10].

One of the most popular organic PCM is paraffin wax, as it is chemically stable, does not degrade after repeated melt/solidify cycles and has a thermal energy storage capacities about 200 J/g. PCM can be produced in various chemical formulations and therefore with different melting temperatures. Some drawbacks of paraffin wax are its relatively low thermal conductivity and a considerable volume increase during melting.

The drying process shows two stages: (i) convective heat transfer towards the surface of the wet substrate followed by the conductive transfer of energy inside the substrate; and (ii) mass transfer from the core of the substrate towards the surface, followed by the withdrawal of water from the surface. The drying air absorbs the water only if its relative humidity is below saturation. Temperature control is relevant especially for thermo-labile foodstuffs, since the quality attributes can be impaired [5,6].

Solar drying can be classified in (a) direct and (b) indirect. Although the first one may be efficient and cheaper, it has disadvantages such as contamination with dirt, insects and microorganisms. In order to avoid these drawbacks, the foodstuff is located in a drying chamber, and receives energy indirectly from the drying

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Nomenclature

a^*	color parameter (–)
b	color parameter (s/m)
b^*	color parameter (–)
c	dimensionless parameter (–)
D_{eff}	effective moisture diffusivity (m^2/h)
E	color parameter (–)
F	force (Newton)
I	radiation (W/m^2)
k	Page's parameter (–)
k_1	Peleg's constant (s kg_{db}/kg_{water})
k_2	Peleg's constant (kg_{db}/kg_{water})
L	half thickness characteristic of the mushroom slices (m)
L^*	color parameter (–)
m	mass (kg)
n	Page's model parameter (–)
N	number of experimental runs (–)
Q	air flow rate (m^3/θ)
Q	heat (J/s)
R	air recycle level (%)
RH	relative air humidity (–)
RMSE	root mean squared deviation (–)
T	drying air temperature (°C, K)
t	time (s)
X	average moisture content (water kg/kg wb)
X_o	initial moisture content (water kg/kg wb)
X_{eq}	equilibrium moisture content (water kg/kg wb)
Greek letters	
Δ	difference between two values
ρ_p	density of the particle (kg/m^3)
ρ_b	bulk density of particles (kg/m^3)
μ	air viscosity (kg/m s)
Sub-indexes	
c	critical
o	initial
amb	ambient
sp	solar panel outlet
eq	equilibrium

air. In recent years, the use of solar dryers has been popularized in rural communities with high solar radiation levels.

Hybrid solar dryers consist of three main components: (a) a solar panel to capture solar energy, (b) electric resistances and/or an energy accumulator, and (c) a drying chamber [1]. Different studies about hybrid solar dryers are available, considering dryers with and without solar energy accumulation system. These studies showed that the solar energy contributes between 10% and 25% of the total energy input [11–16].

Mushrooms have a high nutritional value and a low caloric input, and also a high content of vitamins, minerals, essential amino acids and dietary fiber. In Chile, mushroom consumption increased in the last years, with a consumption of 0.4 kg per capita, a relatively low value compared with other countries such as Taiwan and the Netherlands, with consumption above 6.5 kg per capita. The shelf life of mushrooms stored at 6–8 °C is relatively short, fluctuating between 7 and 10 days. An alternative way to preserve is dehydration, but given that mushrooms are thermo labile, drying conditions must be mild.

The aim of this work was to extend the recent study published by Reyes et al. [15] by increasing the thickness of mushroom slices up to 12 mm and including some modifications in the dryer, specifically increasing the solar panel surface from 3 to 10 m^2 and incorporating a paraffin wax as phase change material (PCM) in the solar energy accumulator. The quality of the final product (color, shrinkage, rehydration and texture), as well as thermal efficiency of the panel and the accumulator were determined.

2. Fundamentals aspects

2.1. Drying models

The Fick's second law, which can be integrated for unidirectional geometries (infinite slab, infinite cylinder and sphere) and different initial and boundary conditions, allows describing phenomenologically the mass transfer processes based on effective diffusivity (D_{eff}) [16]. Convective drying of agroproducts produces an increase of the solid temperature and a notorious shrinkage, resulting in a variation of D_{eff} during the process. Simplifications for analyzing the drying process consider that air conditions and D_{eff} remain constant, that shrinkage and external mass transfer resistance are neglectable. Additionally, since equilibrium moisture content (X_{eq}) is low, it can be neglected. With these approximations, for an infinite slab of 2L thickness and diffusion in the 'x' direction, the Constant Diffusivity Model (CDM) is expressed as follows:

$$\frac{X(t)-X_{eq}}{X_o-X_{eq}}=\frac{X(t)}{X_0}=\frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}\exp\left[-(2n-1)^2\frac{\pi^2}{4L}\cdot\left(\frac{D_{eff}\cdot t}{L}\right)\right] \quad (1)$$

By omitting the factor $8/\pi^2$ and considering only the first term of the series, the Simplified Constant Diffusivity Model (SCDM) is obtained, which is given by Eq. (2). The SCDM allows an estimation of D_{eff} [17]:

$$\frac{X(t)}{X_o}=\exp\left(-\frac{\pi^2}{4L^2}\cdot D_{eff}\cdot t\right) \quad (2)$$

Drying of agroproducts is usually accompanied by a significant shrinkage, caused by changes in the microstructures due to moisture content gradients [17,18]. This shrinkage can be described in terms of solid semi-thickness as a function of drying time, thus making it possible to include a function that describes the semi-thickness in terms of time or moisture content, $L(t)$.

On the other hand, the drying kinetics of agro-products can be described also by empirical models. Among them, the most popular one is the Page's model, given by Eq. (3) [19].

$$\frac{X(t)}{X_0}=\exp(-k\cdot t^n) \quad (3)$$

2.2. Rehydration models

The aim of rehydration is to recover the original sensorial attributes of the product, by soaking it in water [20,21].

The rehydration kinetics is usually described through the Fick's second law [16]. Considering an infinite slab geometry, constant D_{eff} and neglectable swelling, Eq. (4) is obtained: