Journal of Food Engineering 175 (2016) 33–42

Contents lists available at ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

A thermodynamic model for hot air microwave drying of orange peel

Clara Talens [a], Marta Castro-Giraldez [b], Pedro J. Fito [b, *]

[a] AZTI - Food Research, Parque Tecnológico de Bizkaia, Astondo Bidea, Edificio 609, Derio 48160, Bizkaia, Spain
[b] Instituto Universitario de Ingeniería de Alimentos para el Desarrollo, Universidad Politécnica de Valencia, Camino de Vera s/n, Valencia 46022, Spain

ARTICLE INFO

Article history:
Received 29 April 2015
Received in revised form
1 October 2015
Accepted 1 December 2015
Available online 10 December 2015

Keywords:
Hot air–microwave drying
Orange peel
Thermodynamics

ABSTRACT

The citrus juice industry produces a great amount of waste that needs innovation and development to become products. There is a continuous demand to develop innovative approaches for the valorization of citrus by-products by applying environmentally and economically sustainable processes. One of the critical steps for by-products stabilization is the drying operation. The aim of this work was to develop a thermodynamic model for understanding internal heating and water transport mechanisms occurring from the inside to the outside of orange peels during hot air-microwave drying, and to predict the chemical and structural transformations. Different microwave energies (2, 4 and 6 W/g) combined with hot air (HAD) at 55 °C were used for drying citrus peels (5, 15, 40, 60 and 120 min). Mass, volume, surface, water activity, moisture, and permittivity were measured in fresh and dried samples. A thermodynamic model was developed to explain the mechanisms involved in mass and energy transports throughout the combined drying by hot air and microwave. This model allows optimizing the traditional hot air drying, by coupling microwave, of orange peel waste as a novel process for citrus by-products valorization, reducing the process time and therefore process costs.

1. Introduction

Thermodynamics are vital to financially ensure food production due to process variability with time, food heterogeneity, natural variation, complex geometry and temperature dependence of food properties. Drying involves the simultaneous transfer of mass and energy and it is a classical method of food preservation (Orsat et al., 2007), especially for vegetable by-products which are important sources of bioactive compounds such as antioxidants and dietary fiber (Larrauri, 1999).

The second law of thermodynamics involves the reversibility or irreversibility of processes and is very important to follow the changes of enthalpy (total heat) of material as heat is added or removed. In the drying industry, the goal is to use a minimum amount of energy for maximum moisture removal for the desired final conditions of the product. In order to find out the energy interactions and thermodynamic behavior of drying air throughout a drying chamber, heat balances should be performed by applying the first and second law of thermodynamics (Akpinar et al., 2006).

Drying of fruits and vegetables has been traditionally achieved by hot air drying (HAD) (Nijhuis et al., 1998). However, drying may cause irreversible modifications to the cell wall polysaccharides, affecting their original structure and composition, and therefore the final quality of the dried vegetable by-product (Femenia et al., 2003). Energy consumption is another critical issue in the selection of a process and with the increase in fuel prices it becomes an important factor to consider. Applying microwave energy (MW) to a drying process provides an efficient mean of transferring energy for moisture removal (Orsat et al., 2007). Microwave drying uses electromagnetic energy in the frequency range of 300 MHz to 300 GHz, being 2450 MHz the most commonly used frequency in Europe and 915 MHz in USA. Microwaves are generated inside a cavity by stepping up the alternating current from domestic power lines up to 2450 MHz (Orsat et al., 2005).

Tulasidas et al. (1995) demonstrated that the use of microwave energy combined with hot air for drying had relatively low energy consumption, because reduces the drying time in compare with traditional drying. Therefore, the volumetric heating and the consequent reduction of drying time make microwaves an attractive source of thermal energy.

In microwave drying, heat is generated within the product through dipolar molecular induction and orientation caused by the alternating electromagnetic field. The generated water vapor must be coupled to a gradient of water chemical potential, in order to

* Corresponding author.
E-mail address: pedfisu@tal.upv.es (P.J. Fito).

http://dx.doi.org/10.1016/j.jfoodeng.2015.12.001

Notation

a_j	activity of the chemical specie j (–)
R	ideal gases universal constant (J mol $^{-1}$ K^{-1})
q	heat (kJ s^{-1})
T	temperature (K)
s	molar partial entropy (J K^{-1} mol^{-1})
S	entropy (J K^{-1})
P	absolute pressure (Pa)
V	volume (m^3)
l	elongation (m)
L	phenomenological coefficient (mol^2 J^{-1} s^{-1} m^{-2})
n	number of moles (mol)
M	mass (kg)
Mr	molecular weight (g mol^{-1})
A	surface (m^2)
J	molar flux (mol s^{-1} m^{-2})
t	time (s)
G	free energy (J)
e	charge (C)
E	energy (W g^{-1})
C_P	specific heat (W g^{-1} K^{-1})
X	absolute moisture (kg_w kg_{da}^{-1})
f	frequency (Hz)
c	light speed (m s^{-1})
H	overall enthalpy (J)
h	partial enthalpy (J kg^{-1})
r, y	distribution ratio
x	mass fraction (kg kg^{-1})

Greek variables

ε	permittivity (–)
ε′	dielectric constant (–)
ε”	loss factor (–)
Ψ	electric potential (J mol^{-1} C^{-1})
μ_j	chemical potential of the specie j (J mol^{-1})
ν_j	molar partial volume of the specie j (L mol^{-1})
ϕ	relative humidity (–)
β	penetration depth

Subscripts

T	total
air	air
w	water
t	process time
0	initial time
i	any chemical species
HAD	hot air drying
MW	microwave power
Abs	absorbed

Superscripts

n	number of samples
i	interface
v	vapour
HAD	hot air drying
MW	microwave
da	dry air

remove it, by using an external air with low relative humidity. Therefore, this process is a combination called ‘hot air-microwave drying’ (Orsat et al., 2007). A combination of hot-air drying and microwave process has proven to reduce drying time while improving product quality and minimizing energy requirements (Erle, 2005; Funebo and Ohlsson, 1998; Holtz et al., 2010; Igual et al., 2012; Soysal et al., 2006; Tulasidas et al., 1995). The heat flux, induced by the air temperature gradient, is conducted through the product beginning in the surface, nevertheless in case of microwave heating, the energy is absorbed with certain penetration depth.

Castro-Giraldez et al. (2011a,b) suggested considering food as a cellular system, consisting in extracellular space or apoplastic ways, cells with the major quantity of water inside joined with the symplastic ways. Inside the tissue, these authors proposed to share out the liquid water in liquid phase and in the adsorbed water. Therefore, any consideration in mass or energy transport must reflect this point of view and respect the complexity of vegetal tissue.

The mechanisms involved in the microwave-biological systems interaction are dipolar rotation and ionic conductivity. The permittivity of a biological tissue determines how many quantity of electric energy absorbed is distributed in electric energy stored (as a battery) or in mechanical and thermic energy dissipated. Therefore, vectorial permittivity (expressed as complex number, ε = ε’-jε”) is necessary to quantify the overall heating produced when any food product is exposed to microwave radiation. This physical property defines the interaction between the biological systems and the electric field. The real part, ε′, is called dielectric constant, and represents the proportion of electric energy absorbed and stored. The imaginary part, the loss factor, ε”, represents the proportion of electric energy absorbed that is dissipated in other energies, such as mechanical or thermal (Traffano-Schiffo et al., 2015).

Physical or mathematical models are important for simulating what happens during the process and therefore to predict the values of the desired properties. The potential use of citrus by-products in different technological applications involves some type of processing, i.e.,dehydration, which can alter their functional properties by affecting its hydration capacity. Garau et al. (2007) concluded that air-drying temperature should be controlled in order to preserve the quality of dietary fiber and antioxidant capacity of orange by-products as they might be degraded or modified either when extended drying periods and/or high drying times are applied.

The aim of this work was to develop a thermodynamic model for understanding internal heating and water transport mechanisms occurring from the inside to the outside of orange peels during hot air-microwave drying, and to predict the chemical and structural transformations.

2. Materials and methods

Oranges (*Citrus sinensis* (L.) Osbeck var Washington Navel) were bought from a local supermarket in Valencia (Spain). Orange peels were used for the experiments. 60 orange peel cylinders (20 mm diameter and 3 mm thickness) were cut with a core borer. The size and shape of the samples was selected trying to simulate the small pieces of orange peels obtained after the mechanical extraction of juice and the cut by a hammer crusher machine in the processing of orange peel.

A diagram of the experimental procedure is shown in Fig. 1.

Samples were subjected to hot air drying (HAD) and microwave assisted air drying (HAD + MW) (Fig. 2), using a specially designed