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Model-based investigation into atmospheric freeze drying assisted by power ultrasound

J.V. Santacatalina [a], D. Fissore [b], J.A. Cárcel [a], A. Mulet [a], J.V. García-Pérez [a,*]

[a] *Grupo ASPA, Departamento de Tecnología de Alimentos, Universitat Politècnica de València, Camí de Vera s/n, E46022 València, Spain*
[b] *Dipartimento di Scienza Applicata e Tecnologia, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy*

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ABSTRACT

Atmospheric freeze drying consists of a convective drying process using air at a temperature below the freezing point of the processed product, and with a very low relative humidity content. This paper focuses on the use of a simple one-dimensional model considering moving boundary vapor diffusion to describe the ultrasonic assisted atmospheric freeze-drying of foodstuffs. The case study is the drying of apple cubes (8.8 mm) at different air velocities (1, 2, 4 and 6 m/s), temperatures (−5, −10 and −15 °C), without and with (25, 50 and 75 W) power ultrasound application. By fitting the proposed diffusion model to the experimental drying kinetics, the effective diffusivity of water vapor in the dried product was estimated. The model was successfully validated by drying apple samples of different size and geometry (cubes and cylinders). Finally, a 2^3 factorial design of experiments revealed that the most relevant operating parameter affecting the drying time was the applied ultrasound power level.

1. Introduction

Atmospheric freeze drying (AFD) consists of a convective drying process where the temperature of the air has to be kept below the freezing point of the processed material, and the relative humidity has to be, in general, very low. Since the air is not saturated with water vapor, a vapor partial pressure gradient is created between the product and the air, forcing the ice to sublimate and the water vapor to diffuse to the air (Meryman, 1959; Bantle and Eikevik, 2011). AFD is generally carried out at temperatures of between −10 °C and the initial freezing point of the product, as this appears to be a good compromise between costs and final product quality (Wolff and Gibert, 1990a, 1990b; Claussen et al., 2007a, 2007b). The advantages of AFD are its lower cost compared to vacuum freeze drying and the possibility of its being carried out as a continuous process, thus also allowing energy recovery (Bantle et al., 2011).

In cold regions, the AFD process has a long history of use as a means of food preservation (Rhamann and Mujumdar, 2008a), although Meryman (1959) was the first to report the potential of AFD. Stawczyk et al. (2007) investigated the freeze-drying kinetics and the product quality of apple cubes in a fully automated heat pump-assisted drying system. Their results showed that the rehydration kinetics and the hygroscopic properties of the product were similar to those obtained by vacuum freeze drying. These findings agreed with the work of Claussen et al. (2007c), which was carried out using heat pump fluidized bed and tunnel dryers. However, despite the promises of low energy consumption and a better quality product, certain problems still exist in the atmospheric freeze-drying process, limiting its practical implementation. Furthermore, due to the low vapor diffusivity at atmospheric pressure, AFD is controlled by the internal resistance to heat and mass transfer, making it a long drying process (Rhamann and Mujumdar, 2008b).

Since the main drawback of the AFD process is the low sublimation rate, improving mass transfer would be beneficial. In the last few years, new power transducers with extensive surface radiators have been developed for applications in gas media (Gallego-Juárez et al., 2001), such as de-foaming and air drying. Thus, high-intensity airborne ultrasound application brings about mechanical effects when the sound wave is directed into the product (Bhaskaracharya et al., 2009), which intensify the drying of foodstuffs (Gallego-Juárez et al., 2007; Gallego-Juárez, 2010; Riera et al., 2011). Therefore, high-intensity airborne ultrasound was suggested as a potential technology for improving mass transfer in AFD by Cárcel et al. (2011). Ozuna et al. (2014) and García-Pérez et al. (2012) have also shown the feasibility of employing power ultrasound to accelerate the drying kinetics of fruits,

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[*] Corresponding author. Tel.: +34 963879376; fax: +34 963879839.
E-mail address: jogarpe4@tal.upv.es (J.V. García-Pérez).

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Nomenclature

S	surface of the product, m^2
a	parameter used to calculate the heat transfer coefficient
$c_{p,air}$	air specific heat, J/kg K
D_e	effective diffusivity of water vapor in the dried product, m^2/s
G	sublimation flow rate, kg/s
ΔH_s	heat of sublimation, J/kg
J_w	sublimation flux, kg/s m^2
j_h	*j-factor* for the heat transfer
L_0	initial characteristic dimension of the product, m
L_{dried}	characteristic dimension of the dried product, m
M_w	water molecular weight, kg/kmol
n	parameter used to calculate the heat transfer coefficient
p_w	water vapor partial pressure, Pa
$p_{w,c}$	water vapor partial pressure in the drying chamber, Pa
$p_{w,i}$	water vapor partial pressure at the sublimation interface, Pa
p_w^*	water vapor partial pressure at the external surface of the product, Pa
Q	heat flow rate, W
R	ideal gas constant, J/kmol K
Re	Reynolds number
r	radial coordinate
T	temperature, K
T_{air}	air temperature, K
T_i	temperature of the sublimation interface, K
t	time, s
V_{dried}	volume of the dried product, m^3
W	water content in the product, $kg_{water}/kg_{dry\ matter}$
W_0	water content in the product at the beginning of the drying process, $kg_{water}/kg_{dry\ matter}$
W_f	water content in the product at the end of the drying process, $kg_{water}/kg_{dry\ matter}$
x	axial coordinate, m

Greek letters

α	mass transfer coefficient, m/s
β	heat transfer coefficient, W/m^2 K
λ_{dried}	thermal conductivity of the dried product, W/m K
ρ_{air}	density of the air, kg/m^3
ρ_{dried}	density of the dried product, kg/m^3

vegetables and fish at low temperatures. The latter have achieved a maximum drying time reduction of 77% by applying power ultrasound during the drying of apple at −10 °C.

Mathematical modeling represents an important tool in the analysis of the drying process and the operation of the dryer (Mulet et al., 2010). Several empirical, semi-empirical, and analytical equations have been reported for predicting the drying curves for different products and operating conditions. However, there are few first principle models which have been reported to thoroughly describe the AFD process and even less effort has been made to assess its adequacy. One of these models is based on the Lewis equation and its accuracy depends greatly on the accurate evaluation of the thermal properties in the structure of the dried product (Claussen et al., 2007b). Rahman (2009) also suggested a method based on the thermal properties of the product and used the analogy between Nusselt and Sherwood numbers to predict the drying rate in AFD. A similar approach was taken by Li et al. (2007), where a CFD model for an AFD process of apple was developed. When also working on the AFD of apple cubes, Stawczyk et al. (2007) observed that no first drying stage or constant drying rate occurred, and the complete dehydration process was controlled by internal water diffusivity. A similar conclusion was also drawn by Di Matteo et al. (2003). An analytical solution for AFD is presented by Wolff and Gibert (1990a, 1990b) where the “Uniformly Retreating Ice Front” (URIF) approach is coupled to the laws of heat and mass transfer. In the URIF model, the product is divided into two layers; a frozen (or wet) inner core and an outer dry layer. It is assumed that the drying occurs as a consequence of the frozen core gradually shrinking down to zero. Heat is transported from the surface of the product, causing sublimation at the ice front. The resulting water vapor is transported back to the surface and to the gas medium.

In this context, the main goals of this work were to evaluate the feasibility of a simple one-dimensional model to describe the ultrasonic assisted AFD process of apple cubes, as well as to validate such a model in different operating conditions. Finally, a suitable design of experiments coupled with the analysis of the effects was used to point out the key parameter for the atmospheric freeze drying process, which would positively contribute to further optimization stages.

2. Materials and methods

2.1. Raw material

Apples (*Malus domestica* cv. Granny Smith) were purchased in a local market (Valencia, Spain). Fruits were selected to obtain a homogeneous batch in terms of ripeness, size and color, and held at 4 °C until processing. Cubic samples (8.8 mm and 17.5 mm side) were obtained from the flesh using a household tool. Cylindrical samples (height 40 mm and diameter 15 mm) were also prepared using a 15 mm hole puncher. All the samples were wrapped in plastic film and frozen at −18 ± 1 °C until processing (at least 24 h). The initial moisture content was measured by placing the samples in a vacuum oven at 70 °C and 200 mmHg until constant weight was reached, following the standard method 934.06 (AOAC, 1997).

2.2. Drying experiments

Drying experiments were carried out in a convective drier with air recirculation (Fig. 1), already described in the literature (García-Pérez et al., 2012). The drier provides an automatic temperature and air velocity control. A cylindrical radiator (internal diameter 100 mm, height 310 mm, thickness 10 mm) driven by a power ultrasonic transducer (frequency 22 kHz, power capacity 90 W) was used as the drying chamber. The transducer generates an ultrasonic field inside the cylinder, which interacts with the samples and the surrounding air during drying. Air goes through the cylindrical radiator where samples were randomly placed in a holder for assuring a uniform treatment of them for both air flow and ultrasound application. A set of experiments was carried out to determine the drying kinetics of apple cubes (8.8 mm) at different air velocities (1, 2, 4 and 6 m/s), temperatures (−5, −10 and −15 °C), without and with (25, 50 and 75 W) power ultrasound (US) application. Another set of experiments was carried out with larger apple cubes (17.5 mm). In this case, the drying conditions used were -10 °C, 2 m/s and without US application.

In every experiment, the samples were weighed at preset times and the relative air humidity was kept at under 15 ± 5%. For each