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Air-borne ultrasound application in the convective drying of strawberry

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ABSTRACT

The use of non-thermal technologies, such as power ultrasound, is mostly suitable for the drying of thermolabile food materials. Thereby, the air-borne ultrasonic application as a means of improving the convective drying of strawberry has been explored in this work. Experiments were conducted by setting the acoustic power applied (0, 30 and 60 W) and the air temperature (40, 50, 60 and 70 °C). The desorption isotherms and the shrinkage pattern were also experimentally determined. In order to describe the drying kinetics, a diffusion model considering both convective transport and shrinkage was used.

The increase in both the applied acoustic power and temperature gave rise to a significant reduction of drying time (13–44%). The application of power ultrasound involved a significant ($p < 0.05$) improvement in the effective moisture diffusivity and the mass transfer coefficient, the effect being less intense at high temperatures. The results reported here highlight the fact that ultrasonic application during convective drying is a promising supporting technology with which to reduce the drying time needed for heat sensitive products, such as strawberry.

1. Introduction

Over many decades, convective drying using hot air has been considered as the conventional dehydration method for foodstuffs since it extends shelf life and makes the low cost transportation and storage of the dry material easier. Despite being the most widely-addressed technique, hot air drying is considered one of the most energy intensive industrial operations. Thus, it is estimated that thermal dehydration processes account for up to 25% of the industrial energy consumption in developed countries (Chen and Mujumdar, 2008).

In order to understand the drying process and be able to improve it, mass transfer phenomena have been studied and the controlling resistances taken into account (Bon et al., 2007; Giner, 2009; Ozuna et al., 2011; Barati and Esfahani, 2013). Water transfer is mainly controlled by the rate of the water movement inside the materials (internal resistance, IR) and the convective transport from the solid surface to the air (external resistance, ER). The internal resistance is characteristic of the food material, while the external one depends mostly on the thickness of the diffusion boundary layer (Cárcel et al., 2007). Despite the great efforts made to improve the drying process, it is known that optimal requirements for the heat and mass transfer do not necessarily ensure the final products are of optimal quality.

During hot air drying, product quality loss is linked to the use of high temperatures and long drying times. Thus, the limitations to a conventional drying process could be partially overcome by using additional energy sources, such as microwave (Li et al., 2011), infrared radiation (Rastogi, 2012) or power ultrasound (US) (Cárcel et al., 2012; Chandrapala et al., 2012), which should help to reduce both drying time and temperature. In the case of microwave or infrared radiation, there is a risk of product overheating, which has to be considered when the drying of heat-sensitive products is addressed. On the contrary, US waves mainly produce mechanical effects and their air-borne application can intensify the water removal without introducing a high amount of thermal energy during drying (Riera et al., 2011). This represents a great improvement in the field of non-thermal processing and environmentally-friendly, energy-saving technologies. In fact, it is acknowledged that US technology is a good example of how to ensure sustainability (Gallego-Juarez, 2010). Moreover, the fact that applying power US in gas media only produces a low thermal effect means that its application in the drying of heat-sensitive materials is of interest (Awad et al., 2012; Cárcel et al., 2012; Chemat et al., 2011). The ultrasonic effects in gas–solid systems are mainly linked to the rapid series of alternative compressions and expansions promoted by the ultrasonic waves in both the solid particle ("sponge effect") and the surrounding air. This mechanical force can create microscopic channels that allow an easier inner water movement (De la Fuente et al., 2006), as well as microstreaming and high turbulence at the interfaces (Cárcel et al., 2012). Additionally, the phenomenon of

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Nomenclature

a_w	water activity
C	BET's model parameter
DM	dry matter
D_e	effective moisture diffusivity (m^2/s)
D_0	pre-exponential Arrhenius factor
E_a	activation energy (kJ/mol)
k	mass transfer coefficient (kg W/m^2/s)
L	mass transport characteristic dimension (m)
N	number of experimental points
R	universal gas constant (kJ/mol/K)
S_w^2	variance of experimental moisture $(\text{kg W/kg DM})^2$
S_{tw}^2	variance of moisture estimation $(\text{kg W/kg DM})^2$
t	time (s)
T	temperature (K)
V	volume (m^3)
VAR	explained variance
W	moisture content (kg W/kg DM)
x	mass transport characteristic direction
ρ_{ds}	dry solid density (kg DM/m^3)
φ_{air}	relative humidity of the drying air

Subscripts

calc	calculated
exp	experimental
m	monolayer
0	initial
p	local

cavitation could provoke the removal of the most strongly attached water molecules (Soria and Villamiel, 2010). Recent studies have reported how air-borne US application in food drying is greatly affected by both the operational parameters and product properties (Ozuna et al., 2011). These studies have addressed the US application in the drying of lemon (García-Pérez et al., 2009) and orange peel (Ortuño et al., 2010; García-Pérez et al., 2012), olive leaves (Cárcel et al., 2010), potatoes (Ozuna et al., 2011) and carrots (Cárcel et al., 2011), among others. However, to the best of our knowledge, there have been no previous studies into the ultrasonically assisted convective drying of berries. Strawberries are fruits which enjoy wide consumer acceptance not only due to their palatability but also to their nutritive value and bioactivity (Giampieri et al., 2012), making strawberries one of the largest fruit crops (Doymaz, 2008).

The aim of this paper was to assess the influence of the air temperature and the application of ultrasound on the convective drying kinetics of strawberry. For that purpose, experimental results were analyzed and modeled using the diffusion theory.

2. Materials and methods

2.1. Samples preparation

Fresh strawberries (*Fragaria x ananassa Duch*) were purchased from a local market in Valencia (Spain) and stored at 5 °C for a maximum of 3 days until drying. After washing in tap water, draining with blotting paper and removing the external impurities, strawberries were cut into 2.5 ± 0.5 mm thick slices along their longitudinal axis.

2.2. Moisture content

The moisture content of fresh strawberries was determined at 70 °C and 80 mbar vacuum level until constant weight (AOAC, 1990).

2.3. Airborne US dryer

Strawberries were dried by using an ultrasonic-assisted convective dryer (Fig. 1). The prototype was initially a current pilot-scale convective dryer, with its drying chamber subsequently modified to generate US waves (García-Pérez et al., 2006a; Riera et al., 2011). The ultrasonic device includes a cylindrical vibrating radiator driven by a piezoelectric transducer (21.8 kHz), which generates a high-intensity ultrasonic field in the air medium, where the samples are placed. A high power US generator, an impedance matching unit and a digital power meter (WT210, Yokogawa Electric Corporation, Japan) regulate and measure the electrical parameters of the acoustic signal (voltage, intensity, phase, frequency and power). The air parameters (velocity and temperature) were controlled through a PID algorithm and a PC supervised the whole drying process.

2.4. Drying experiments

An air velocity of 2 m/s was chosen for drying experiments of strawberry slabs, according to previous studies carried out in the same dryer (Cárcel et al., 2007; García-Pérez et al., 2006a, 2009). The temperature ranged between 40 and 70 °C (Table 1), which could be considered mild drying temperatures. Two levels of

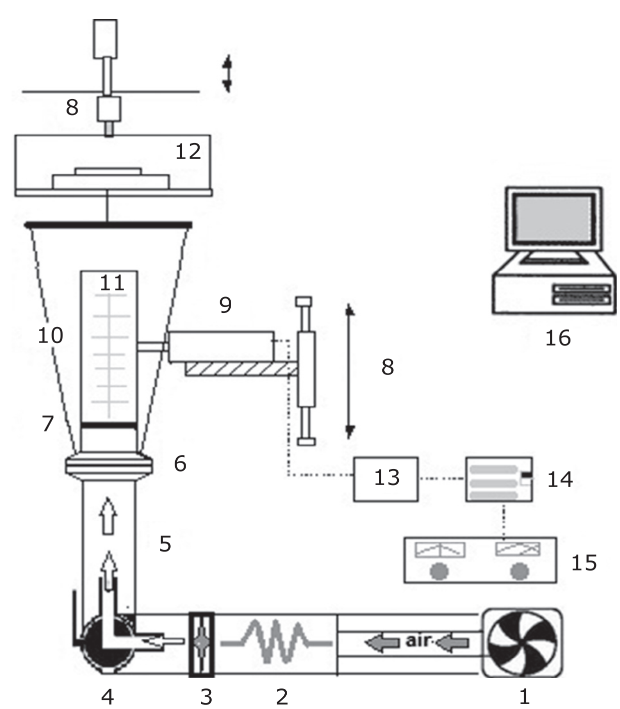

Fig. 1. Diagram of the ultrasonic assisted dryer. 1. Fan. 2. Heating unit. 3. Anemometer. 4. Three-way valve. 5. Thermocouple. 6. Sample loading chamber. 7. Coupling material. 8. Pneumatic system. 9. Ultrasonic transducer. 10. Vibrating cylinder. 11. Trays. 12. Balance. 13. Impedance matching unit. 14. Digital power meter. 15. High power ultrasonic generator. 16. PC.