Journal of Food Engineering 127 (2014) 93–102

Contents lists available at ScienceDirect

Journal of Food Engineering

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

Influence of high-intensity ultrasound on drying kinetics in fixed beds of high porosity

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ARTICLE INFO

Article history:
Received 12 July 2013
Received in revised form 28 November 2013
Accepted 2 December 2013
Available online 11 December 2013

Keywords:
Food drying
Heat and mass transfer
Mathematical modeling
Ultrasound assisted drying

ABSTRACT

Hot air drying is an energy intensive process and can affect bioactive components. A common method of food drying is in a fixed bed. The application of high-intensity ultrasound could constitute a way of improving traditional convective drying systems. Therefore, the main aim of this work was to assess the influence of high-intensity ultrasound on transfer phenomena during the convective drying in a high-void bed of non-porous materials, like thyme leaves. For this purpose, drying kinetics of thyme leaves were carried out at 1, 2 and 3 $\mathrm{m\,s^{-1}}$ air velocity at different air temperatures (40, 50, 60, 70, and 80 ± 1.2 °C), and different levels of acoustic power density (0, 6.2, 12.3, 18.5 $\mathrm{kW\,m^{-3}}$). To address the effect of US on the drying kinetics, a mathematical model was developed considering time varying boundary conditions for heat and mass transfer between the air and the product. Due to the physical characteristic of the material, the influence of the ultrasound power density applied on the internal resistance to the mass transfer was significantly lower than its influence of the external resistance; therefore process intensification is mainly linked to external resistance. Nevertheless, the influence of the application of ultrasound on transport phenomena was only observed at air temperatures and air velocities below 70 °C and 3 $\mathrm{m\,s^{-1}}$ respectively.

1. Introduction

Drying, a process in which heat and mass transfer processes are present, is one of the oldest and most important methods of food preservation known to man (Akpinar, 2006). Despite the fact that hot air drying is a widely used method, it does present some quality and energy limitations which may be considered as challenges if the process is to be improved. These limitations can be found in the changes in the biochemical properties of foodstuffs, causing the deterioration of aroma compounds (Timoumi et al., 2007), the degradation of nutritional substances browning and color loss (Suvarnakuta et al., 2005), among other things.

The introduction of new drying technologies could lead to a shortening of the processing time, thus improving both the energy efficiency of drying operations and the quality of the dried products (Chou and Chua, 2001). High-intensity airborne sonic and ultrasonic waves have been used to intensify the drying rate of materials. The acoustically assisted hot air drying process permits the use of lower temperatures and may be useful for drying heat-sensitive materials (Gallego-Juarez et al., 2007).

It could be of importance for the industry to improve the drying process in order to preserve the bioactive components of foods. Those ingredients that can be obtained from thyme leaves appear to be an interesting ingredient for food formulation.

The use of ultrasonic energy is very promising because it can act without affecting the main characteristics and quality of the products. Ultrasound introduces pressure variations, oscillating velocities and microstreaming at the interfaces, which may modify the diffusion boundary layer. As a consequence, ultrasound may affect both external and internal resistance to mass transfer. It is known that ultrasound effects are product-dependent and are related to product porosity (García-Pérez et al., 2011, 2009). As a consequence, it is of interest to analyze ultrasound-intensifying effects in porous beds of non-porous materials, like leaves.

The convective drying of foods in fixed beds of high porosity is an important application. The complexity of the process arises from the simultaneous heat and mass transfer between the air and the product. In order to address this complexity, it is necessary to model the process adequately. Several models have been formulated to describe the heat and mass transfer processes during fixed bed drying. These models include either simplified or rigorous models. The simplified models are mainly based on the assumption of a dominant mechanism for heat and mass transfer.

Rigorous mathematical representations have been developed for the batch drying of foodstuffs from the non-steady state heat and mass balances in a differential element of the fixed bed (Istadi and Sitompul, 2002; Herman-Lara et al., 2005).

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http://dx.doi.org/10.1016/j.jfoodeng.2013.12.002

Nomenclature

A	leaf area (m^2)
Cp_{da}	specific heat of dry air ($J\ kg^{-1}\ K^{-1}$)
Cp_v	specific heat of vapor ($J\ kg^{-1}\ K^{-1}$)
Cp_w	specific heat of water ($J\ kg^{-1}\ K^{-1}$)
Cp_{ds}	specific heat of the dry solid ($J\ kg^{-1}\ K^{-1}$)
D	effective water diffusivity in the sample ($m^2\ s^{-1}$)
D_{AB}	diffusivity of water in air ($m^2\ s^{-1}$)
ER	relative error (%)
L	half thickness of the leaves (0.0004) (m)
L_c	thickness of the bed (0.03) (m)
M_{ds}	mass of the dry solid (kg^{-1})
PM_v	molecular weight of water vapor ($kg\ mol^{-1}$)
Q_s	sorption heat ($kJ\ kmol^{-1}$)
R	ideal gases constant ($kJ\ kmol^{-1}\ K^{-1}$)
T	temperature of the solid (°C)
$T(1,t)$	temperature on the leaf surface (°C)
T_a	air temperature (°C)
T_{ae}	air temperature bed exit (°C)
T_{ai}	air temperature bed inlet (°C)
T_{pp}	temperature on the gas–solid interface (°C)
US	acoustic power density ($kW\ m^{-3}$)
V	volume of the bed (m^{-3})
Va	air volume in the bed (m^{-3})
VAR	explained variance (%)
X_a	air moisture content kg kg^{-1}, in d.b.
X_e	moisture content of hot air kg kg^{-1}, in d.b.
X_{eq}	equilibrium moisture content of hot air kg kg^{-1}, in d.b.
a	parameter Eq. (9)
a_w	water activity
b	parameter Eq. (9)
h	heat transfer coefficient ($kW\ m^{-2}\ K^{-1}$)
h_{ae}	air enthalpy ($kJ\ kg^{-1}$)
h_{ai}	hot air enthalpy ($kJ\ kg^{-1}$)
h_{mv}	mass transfer coefficient ($kW\ m^{-2}\ K^{-1}$)
h_w	water enthalpy ($kJ\ kg^{-1}$)
m_a	sry air mass flow ($kg\ s^{-1}$)
m_w	water mass flow ($kg\ s^{-1}\ m^{-2}$)
q	conduction heat flux ($kJ\ s^{-1}\ m^{-2}$)
t	time (s)
x	coordinate (m)
z	simensionless coordinate

Greeks

ε	bed porosity m^3 gas phase m^{-3} bed
κ	thermal conductivity thyme ($kW\ m^{-1}\ K^{-1}$)
κ_a	thermal conductivity air ($kW\ m^{-1}\ K^{-1}$)
λ	latent heat of vaporization, ($kJ\ kg^{-1}$)
v	air velocity ($m\ s^{-1}$)
ρ_{da}	density of the dry air ($kg\ m^{-3}$)
ρ_{dai}	density of the dry air at surface temperature ($kg\ m^{-3}$)
ρ_{ds}	density of the dry solid ($kg\ m^{-3}$)
$\bar{\tau}$	average moisture content of the product kg kg^{-1}, in d.s.
τ	moisture content of the product kg kg^{-1}, in d.s.
τ_{eq}	equilibrium moisture content kg kg^{-1}, in d.s.
τ_0	initial moisture content of the product kg kg^{-1}, in d.s.
ϖ	dimensionless moisture content

Dimensionless numbers

Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
Sc	Schmidt number
Sh	Sherwood number

Although it has been acknowledged that the phenomena involved during drying are complex and that no simple model can account for real behavior, the diffusion theory based on Fick's laws is the most common one with which to describe drying processes during the falling rate period (Mulet, 1994). Diffusion models are built following some assumptions that establish the degree of complexity of the solution. The most common assumptions to consider are related to the effective moisture diffusivity (Maroulis et al., 2001) and the external resistance to mass transfer (Simal et al., 2003).

Several empirical and simple theoretical drying models have been proposed to describe the drying process of thyme (Rodríguez et al., 2013; Doymaz, 2011). However, there is no information in the literature about a time varying boundary conditions model, permitting the description of the high-intensity ultrasound intensifying effects during the convective drying of a bed of thyme leaves.

The aim of this work is to address the transport mechanisms involved in the ultrasonic drying of a porous bed. For that purpose, how the temperature, air velocity and the application of high power ultrasound influenced the hot air drying kinetics of a bed of thyme leaves was analyzed.

2. Materials and methods

2.1. Sample preparation

Fresh thyme samples (*Thymus vulgaris* L.) were obtained (Vivarium Albogarden in Valencia, Spain). The leaves of the plant were plucked manually, and kept in refrigeration (4 °C) in a closed container for their later use. The initial moisture content was 68–70% (w.b), determined according to the AOAC standards (AOAC, 1997). The density of the dry solid was determined using the toluene displacement method.

The physical properties of thyme, dry air and water vapor used in fitting the model are summarized in Table 1.

2.2. Drying experiments

A power-ultrasound assisted convective drier, which was already described in a previous work, was used (Cárcel et al.,

Table 1
Physical properties used in the model solution.

Specific heat of dry air ($kJ\ kg^{-1}\ K^{-1}$) (Pelegrina et al., 1999)
$$Cp_{da} = 2.9275 \times 10^{-7} T_a^3 + 4.7047 \times 10^{-4} T_a^2 + 1.782 \times 10^{-2} T_a + 1005.3$$
Specific heat of water vapor ($kJ\ kg^{-1}\ K^{-1}$) (Pelegrina et al., 1999)
$$Cp_v = 10384.59 - 50.37 T_a + 7.4 \times 10^{-2} T_a^2$$
Water activity (Soysal and Oztekin, 2001)
$$a_w = \exp[-\exp(2.97977 - 0.00258492 T_a^{1.37743}) \tau_{eq}^{-1.44139}]$$
Diffusivity of water in the air phase ($m^2\ s^{-1}$) (Soysal and Oztekin, 2001)
$$D_{AB} = 1.4738 \times 10^{-4} \exp\left(\frac{-523.78}{T_{pp}}\right)$$
Thermal conductivity ($kJ\ m^{-1}\ s^{-1}\ K^{-1}$) for fruits and vegetables (Singh and Heldman, 2001)
$$\kappa = 1.418 \times 10^{-1} + \frac{4.9310^{-1}\tau}{(1+\tau)}$$
Sorption heat (Perry et al., 1997)
$$Q_s = \lambda - \frac{R}{PM_v} \frac{\partial(\ln(a_w))}{\partial(\frac{1}{T_a})}$$
Porosity of the bed
$$\varepsilon = \frac{V_a}{V}$$