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Simulation of grape stalk deep-bed drying

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ABSTRACT

A mathematical representation of grape stalk deep-bed drying with variable air conditions over time and bed positions was developed. The model considers the heat and mass transfer (conduction and diffusion) within the different structures of the grape stalk: three infinite cylinders and one spherical, and the heat and mass balances in the bulk air. The bed was represented assuming ideal mixed stages. A simulator was obtained from the model solution, and validated with experimental drying curves of grape stalk obtained in a plant pilot drier. The simulator adequately predicts the experimental behaviour for grape stalk average moisture and the air output temperature during drying.

1. Introduction

Stalks represent between 3% and 6% of grape weigh, which nowadays is a waste product of the wine industry with scarce economic value (García-Pérez et al., 2006). Grape stalk presents a high content in polyphenol compounds, which are characterized by a significant antioxidant capacity (Spigno and Marco de Faveri, 2007) and as a source of lignocellulosic material (Spigno et al., 2008). The extraction of antioxidant compounds from the grape stalk constitutes a way of making this product a more valuable one, but a drying process prior to the extraction stage is necessary.

The drying process is an operation that needs a high level of energy consumption (at least 2500 kJ/kg of evaporated water), which may be optimized. For this purpose, it is interesting to obtain models that represent the process. However, the mathematical representation may be difficult in products with a complex structure, like the grape stalk. García-Pérez et al. (2006) have made advances in the modeling of grape stalk drying in monolayer by considering the whole structure as a combination of four individual structures: 3 cylindrical and 1 spherical. In addition, these authors evaluated the water diffusivity of the individual structures, and validated the compositional model for the whole grape stalk drying at constant air conditions (García-Pérez et al., 2006).

Deep bed drying implies that air temperature and moisture vary over time and according to the bed position. The air characteristics at the entrance to the drier could be adjusted in order to obtain the maximum thermal efficiency. Therefore the mathematical representation of grape stalk deep-bed drying must consider the heat and mass transfer process within the grape stalk particles, coupled with bulk air, non-steady heat and mass balances in the bed.

The mathematical representation of convective bed drying in which the air conditions vary over time and bed position, has been widely described. The most common consideration for mass transfer is that it is controlled by internal diffusion and, therefore, is calculated from an empirical drying kinetic of the product (Torrez et al., 1998; Marinos-Kouris et al., 1998; Liu and Bakker-Arkema, 2001). Recent studies have improved the ability of models to take into account the heat and mass transfer phenomena involved in deep-bed drying. Zanoleo et al. (2008) use an empirical expression that considers the process state and may include internal diffusion or external convection. Herman-Lara et al. (2005) proposed a similar model but the internal transfer was calculated from analytical solutions of Fourier and Fick's equations. Izadifar and Mowla (2003) introduced external convection for heat and mass transfer and internal diffusion only for mass transfer in the modeling of a rice continuous fluidized bed dryer. García-Alamilla et al. (2007) proposed a mathematical representation that considers both internal and external mass transfer properties during the air drying of cocoa in a rotary drier, assuming ideal mixing in the air phase. As can be observed, the deep-bed drying of complex structures, like grape stalk, has not so far been addressed.

The deep-bed drying of complex particles produces air pressure drops in axial, radial and angular directions due to the surface random distribution of the particles, and therefore, the local air velocity has a random distribution with a dominant flow in the bed's axial direction. Therefore ideal air mixing (García-Alamilla et al.,

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Nomenclature

a	specific surface area, $m^2\,m^{-3}$
a_w	water activity
A	transversal cross-section area, m^2
Cp	specific heat, $J\,kg^{-1}\,K^{-1}$
D	average diffusivity, $m^2\,s^{-1}$
G	air mass flow, kg dry air s^{-1}
h	heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
H	enthalpy, $J\,kg^{-1}$
J	number of nodes in grape stalk particles
K	heat conductivity, $W\,m^{-1}\,K^{-1}$
k_c	mass transfer coefficient, $m\,s^{-1}$
m	shape index: m = 1 (cylinder), m = 2 (sphere)
M	molecular mass, kg $kmol^{-1}$
N	number of ideal bed stages
p	Pressure, Pa
r	particle radial coordinate, m
r^2	regression coefficient
R	particle radius, m
T	temperature, K
v	air velocity, $m\,s^{-1}$
V	volume, m^3
w_0	grape stalk initial mass for drying, kg
X	particle moisture, kg w (kg dry solid)$^{-1}$
Y	air moisture, kg w (kg dry air)$^{-1}$

Greeks symbols

λ	vaporization latent heat, $J\,kg^{-1}$
ε	volumetric fraction,
μ	viscosity, Pa s
ρ	density, $kg\,m^{-3}$

Subscripts

a	for or in air
avg	averaged
b	for drying bulk bed
env	room conditions
i	interface air-solid
j	particle structure index: $\forall j = 1,2,3$: infinite cylinder. j=4: Sphere
k	ideal bed stage index
l	node in particle radial direction
p	for or in particle
s	for dry solid
w	for water
wv	for water vapor

Superscript

0	at reference

Dimensionless numbers

Pr	Prandtl number
Re	Reynolds number for bed
Sc	Schmidt number

2007) may be an appropriate assumption. However, Herman-Lara et al. (2005) have shown that the experimental behaviour of deep-bed drying approximates to the simulation results with plug flow assumption. Then, in order to approximate the drying behaviour to a plug flow one, it is necessary to represent the drying bed as a series of stages each one with ideally mixed air.

Therefore, the aim of this work was to obtain a deep-bed model for grape stalk drying and build and validate a simulator as a first step towards drying optimisation.

2. Model building

As was discussed in Section 1, the deep-bed model assumes ideal mixing of air in a series of stages. Then, the grape stalk deep-bed drying is represented in Fig. 1. The grape stalk moisture and temperature in each stage can be modeled as a monolayer, according to the results of García-Pérez et al. (2006). That is, by assuming four structures: 3 infinite cylinders (with different diameters) and 1 sphere (Fig. 1). Under this assumption the equations obtained were,

Water diffusion within the four structures of grape stalk

$$\frac{\partial \rho_{sp} X_{jk}}{\partial t} = \frac{1}{r^m}\frac{\partial}{\partial r}\left(r^m D_j \frac{\partial \rho_{sp} X_{jk}}{\partial r}\right) \quad \forall j = 1,2,\ldots,4 \quad \text{for } 0 \le r \le R_j, \text{ and } t > 0 \tag{1}$$

where: m = 1 for cylindrical shape ($\forall j = 1,2,3$) and m = 2 for spherical shape (j = 4). Mass transfer boundary conditions consider the convective transfer of water into the drying air from the particle surface ($r = R_j$) and the symmetry at the particle center (r = 0),

$$-D_J \frac{\partial \rho_{sp} X_{jki}}{\partial r} = k_c \rho_a (Y_{jki} - Y_k) \quad \forall j = 1,2,\ldots,4 \text{ at } r = R_j, \text{ and } t > 0 \tag{2}$$

$$\frac{\partial \rho_{sp} X_{jk}}{\partial r} = 0 \quad \forall j = 1,2,\ldots,4 \text{ at } r = 0, \text{ and } t \ge 0 \tag{3}$$

The heat conduction within the four structures of grape stalk is described by,

$$\frac{\partial \rho_p Cp_p T_{pjk}}{\partial t} = \frac{1}{r^m}\frac{\partial}{\partial r}\left(r^m K_s \frac{\partial T_{pjk}}{\partial r}\right) \quad \forall j = 1,2,\ldots,4 \quad \text{in } 0 \le r \le R_j, \text{ and } t > 0 \tag{4}$$

Heat transfer boundary conditions consider the heat flow from the drying air and the heat required to evaporate the water at the particle surface ($r = R_j$), and the symmetry at particle center (r = 0),

$$-K_s \frac{\partial T_{pjki}}{\partial r} = h_a (T_{ajki} - T_{ak}) + k_c \rho_a (Y_{jki} - Y_k)\lambda \quad \forall j = 1,2,\ldots,4 \text{ at } r = R_j, \text{ and } t > 0 \tag{5}$$

$$\frac{\partial T_{pjk}}{\partial r} = 0 \quad \forall j = 1,2,\ldots,4 \text{ at } r = 0, \text{ and } t \ge 0 \tag{6}$$

As observed the effect of air is depicted through interfaces (Eqs. (2) and (5)). The air characteristics were obtained from heat and mass balances in a stage k (Fig. 1). In agreement with García-Alamilla et al. (2007), the non-steady water mass balance in an ideally mixed stage considers the sum of the convective transfer of water on the surface of the four kind of structures into air and the water content of the air flow,

$$\left(1 - \sum_{j=1}^{4} \varepsilon_{bj}\right) V_k \rho_a \frac{dY_k}{dt} = \sum_{j=1}^{4} k_{cwa} \rho_a a_{bj} (Y_{jki} - Y_k) V_k - G(Y_k - Y_{k-1}) \tag{7}$$

The non-steady heat balance in an ideally mixed stage considers the sum of heat fluxes to the surfaces of the four structures, the sum of required heat for water evaporation, the heat flux to drier environment and the heat content of the air flow,