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Drying–toasting of presoaked soybean in fluidised bed. Modeling, validation and simulation of operational variants for reducing energy consumption

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ABSTRACT

Soybeans (*Glycine max*) contribute to healthy nutrition because of the high proportion and quality of proteins. In this work, a bed-level model was developed from kinetic studies carried out earlier, for simulating the drying–toasting of presoaked soybean in a fluidised bed at air temperatures between 100 and 160 °C. The predicted average bed moisture contents and temperatures were validated with purpose-measured experimental data. The air humidity decreased and temperature increased with time at the dryer outlet, approaching the inlet conditions. By using the validated model the thermal efficiency was calculated for bed heights between 0.1 and 0.3 m, considering a system where 90% of the exhaust air was recirculated. The efficiency increased from 9 to 39% at 0.1 m and from 24 to 63% at 0.3 m, indicating that the energy consumption can be substantially reduced. This model is considered useful both for product development and equipment design.

1. Introduction

The drying of biological materials is a complex process where the changes in moisture content and product temperature with time are accompanied by variations of other phenomena as quality and particle structure and size (Akpinar, 2006; Sander, 2006). The trend towards consumption of high-quality foods requires a careful design, simulation and further optimization of the process to reach high energy efficiency as well as to retain quality attributes (Bialobrzewski et al., 2008; Di Scala and Crapiste, 2008).

Soybean (*Glycine max*) is a valuable resource for healthy nutrition due to its elevated content of high quality protein. In view of this potential and considering the growing consumer demand for the intake of dehydrated ready-to-eat snacks (Sun-Waterhouse et al., 2010), a process, by which presoaked soybeans were dried-toasted leading to a stable, low moisture, crispy product, was studied (Torrez Irigoyen and Giner, 2014). The fluidization is a process of contact that takes place between a solid and a fluid (gas or liquid) in which the bed comprising solid particles is agitated by a rising stream of fluid whose pressure drop through the bed is sufficient to support it (Yang, 2003). Fluidised bed technology is increasingly used in the food industry because of its inherently high degree of mixing, which leads to fast and uniform heat transfer in the bed (Alaathar et al., 2013).

Giner and Calvelo (1987) modeled wheat drying in fluidized beds with an analytical solution of the diffusion equation for constant diffusivity and volume coupled with macroscopic heat transfer, combined with macroscopic water and energy balances to calculate the changes of air humidity and temperature. This model has suitably interpreted the experimental data, though a very low thermal efficiency was predicted. Based on this model, Giner and De Michelis (1988) further developed the simulation program to consider air recirculation; they found that the fluidisation process had a high potential for energy recovery.

Madhiyanon et al. (2006) and Markowski et al. (2010) have noted that the modeling of fluidised bed requires the analysis and understanding of the distribution of moisture and temperature inside the grain. Some authors as Jha (2005) and Khalloufi et al. (2010) have pointed out that it is also important understand the changes in drying air absolute and relative humidity,

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Notation

C_p	Specific heat, in J/(kg °C)
H	Enthalpy, J/(mol kg)
L_{w0}	Latent heat of water vaporization at a reference state, J/kg
L_g	Heat of desorption of water in the grain, J/kg
m_{SB}	Mass of dry solid in the bed, kg
n	Number of data points
S	Bed cross sectional area, m^2
t	Time, s
t_d	Total drying–toasting process time, s
T	Temperature, in °C
v	Superficial air velocity, in m/s
W	Bed moisture content, kg water/kg dry matter
x	Absolute humidity, kg water vapor/(kg dry air)
Z_{max}	Bed height, under fixed conditions, m

Greek symbols

Δ	Delta
ε_0	Bed void fraction
ρ	density, kg/m^3

Subscripts

0	Initial
1	Inlet
2	Outlet
a	air
da	Dry air
ds	Dry solid
f	Final
M	Mixed
s	Solids
w	Water
wv	Water vapor
exp	Experimental
pred	Predicted
m	Average

as well as temperature through the bed. On the other hand, Prachayawarakorn et al. (2006) and Martinez et al. (2013) studied hot air fluidisation as an inactivation process although they have not included an interpretation and modeling of the heat and mass transfer phenomena in the bed. However, there are few studies that investigated the energy efficiency of fluidised bed drying and no research dealing with the hot air fluidisation of presoaked soybean was found. Furthermore, regarding to the energy consumption associated with food drying, there is scarce literature dealing with the interplay between mass transfer and heat transfer in the presence of particle shrinkage (Donsí and Ferrari, 1995; Parmar and Hayrust, 2002).

Torrez Irigoyen et al. (2014) has proposed a considerably improved mathematical model of drying–toasting kinetics for presoaked soybean at grain level or thin layer. Local mass transport and variable diffusion coefficient (D_{eff}) were considered, together with variable domain, predicted with a well-founded shrinkage model, relating grain radius with moisture content. The transient temperature curve was predicted by a coupled macroscopic energy balance for this shrinking material. The objectives of this work were (1) to build a bed-level model, by utilizing the grain-level model in the context of an equipment model that simulates fluidized (thick) bed drying toasting, using macroscopic mass (water) and energy balances for drying air around the bed, (2) to validate the predicted bed moisture contents and temperatures as a function of time with purpose-measured experimental data and (3) to carry out simulation exercises to explore the effect of air recirculation on energy consumption for this process.

2. Theoretical considerations

2.1. Model formulation

A mathematical model of fluidised bed drying must be able to predict four fundamental variables as a function of time: the average bed moisture content (W_m), the mean bed temperature (T_{sm}), the air temperature (T_a) and absolute humidity (x_a) at the bed outlet, as a function of time. For this purpose the following assumptions were made:

1) Spherical geometry for the particle;
2) Heat losses from the fluidised bed to the outside are negligible compared with air-grain transfer;
3) Grains are perfectly mixed in the bed;
4) The air leaves the bed in thermal equilibrium with the solids;
5) The superficial air velocity in the bed cross section is uniform.

2.2. Mathematical modeling of drying–toasting in fluidised bed

2.2.1. Microscopic mass balance in the grains

The average grain drying rate ($-dW_m/dt$) is calculated with a local mass balance assuming spherical geometry of soybeans and radial diffusion, variable diffusivity and shrinkage (Torrez Irigoyen et al., 2014). This grain-level average drying rate is converted to a bed-level drying rate by using the following expression

$$m_W^* = m_{SB}\left(-\frac{dW_m}{dt}\right) \quad (1)$$

where

$m_{SB} = \rho_{S0}(1-\varepsilon_0)SZ_{\max}$

2.2.2. Macroscopic balance of water in the bed

The increase in absolute humidity of air as it passes through the bed is due to moisture evaporation from grains; this is represented by the equation:

$$\rho_a v_0 S(x_{a2} - x_{a1}) = m_{SB}\left(-\frac{dW_m}{dt}\right) \quad (2)$$

In Eq. (2) the evaporation rate in the whole bed was computed by multiplying the drying rate and the bed dry mass.

2.2.3. Macroscopic energy balance in the bed

In previous work (Torrez Irigoyen et al., 2014) the analysis was carried out at grain-level (thin layer) without considering modifications in the air phase. Now the bed is thick enough to cause measurable variations in the air conditions. For this reason, the following energy balance across the bed was proposed