Simultaneous heat and mass transfer between air and soybean seeds in a concurrent moving bed

Marcos A. S. Barrozo,* Ana M. Souza, Sônia M. Costa & Valéria V. Murata

Chemical Engineering Department, Federal University of Uberlândia, P.O. Box 593, 38400-902, Campus Santa Mônica, Bloco K, Uberlândia-MG, Brazil

(Received 17 November 1998; Accepted in revised form 2 August 2000)

Summary

The aim of this work was to study the simultaneous heat and mass transfer between air and soybean seeds in concurrent moving bed dryers. The stationary behaviour of the process was described by the mass and energy equations applied to both fluid and particulate phases, assuming uniform velocity of the seeds and flat velocity profile of the air. The results of the fluid-dynamic study confirmed that the velocity of the seeds and air inlet profiles were essentially uniform. The experimental data and simulated values of the temperature of the fluid and temperature and moisture of the seeds were in good agreement.

Keywords

Air velocity, drying, grain dryer, modelling, residence time, temperature.

Introduction

Soybean is currently one of the most important agricultural foods in the world. Its importance in grain production is increasing owing to its high yield capacity and lower harvest costs in comparison with other grains. The soybean produces more protein per hectare than any other crop. This makes it the basic food in the fight against hunger, and it may be found in many densely populated and underdeveloped areas.

The use of moving bed dryers for the drying of seeds is recommended owing to the low investment required and to the energy saving provided by their utilization, when compared with other types of dryers. With respect to the seeds, their use causes less mechanical damage than other types of dryers.

Moving bed dryers are characterized in accordance with the relative directions of seed flow and air flow. Drying employing parallel gas flow, such as concurrent flow, generally leads to more homogeneous moisture and temperature distributions, which is one of the advantages of this configuration. This characteristic is important in order to guarantee the quality of the dried seeds, such as their germinative capacity and vigour.

The simulation of the heat and mass transfer between the air and the grains in a moving bed is generally based on the application of a transport phenomena model to the fluid and solid phases (Brooker et al., 1974; Barrozo et al., 1996a). The goal of this work was to study the simultaneous heat and mass transfer between the air and soybean seeds in a concurrent moving bed, thereby testing the hypotheses that a two-phase model simulated the experimental results. The equilibrium equation and the drying rate and heat-transfer equations were adopted from specific studies by Barrozo et al. (1994), Barrozo et al. (1996b), and Sartori, 1986. Therefore, there was no need to estimate the parameters, because their values had already been defined in previous studies.

Theoretical aspects

Equilibrium moisture

Barrozo et al. (1996b) obtained the equilibrium moisture content of the soybean seeds
experimentally from a static method using saturated salt solutions. The salts were chosen so that a wide range of relative humidity was tested. The isotherms were obtained in the temperature range (34–50 °C) over which the seed quality studies (Barrozo et al., 1996a) displayed the least material damage.

With the aim of finding an equation which represented the behaviour of the experimental equilibrium data, Barrozo et al. (1996b) adopted rival model discrimination. The equations discriminated were those which, according to the literature, best represent the equilibrium data for grains, i.e. the equations of: Henderson (1952), Chung & Pfoest (1967), Thompson et al. (1968), Chen & Clayton (1971) and the modified Halsey equation (Osborn et al., 1989).

The methodology used in the discrimination was based on nonlinearity measurements (Box, 1971; Bates & Watts, 1980; Ratkowsky, 1983). All equations analyzed were nonlinear and in this case some caution is required to estimate parameters. The validity of the statistical inferences of the least square estimators from the nonlinear regression models, like confidence regions, significance levels, confidence intervals of parameters, was assessed by the technique used by Barrozo et al. (1996b).

The results obtained by Barrozo et al. (1996b) showed that the modified Halsey equation was the most appropriate to represent the equilibrium desorption data for soybean seeds.

The modified Halsey equation, with the parameters estimated from equilibrium data obtained by Barrozo et al. (1996b) is:

\[
M_{eq} = (\exp(-0.00672 \cdot T_s + 3.02))/\ln(UR))^{1/1.508}
\]

(1)

where \(M_{eq}\) is the equilibrium moisture content (dry basis fraction), \(UR\) the relative humidity of the air (decimal fraction) and \(T_s\) is the temperature of the solids (°C).

Drying kinetics

The kinetic equation used in this work originated from Barrozo et al. (1994). A thin layer dryer (thickness: 2.7 cm) was used for the kinetic study. The operational characteristics were also chosen to minimize seed damage (air temperature of 34–50 °C and air velocity of 1.0–3.0 m s\(^{-1}\)). A factorial design (Box et al., 1978) in three levels was used in order to study the effect of the drying air temperature and velocity (nine experiments). The diffusive model (equation 2) was used to represent the kinetics data.

\[
MR = \frac{M - M_{eq}}{M_0 - M_{eq}} = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left[-\frac{n^2 \pi^2 D_{ef}^2}{R^2}\right]
\]

(2)

where \(R\) is the particule radius.

The variation of the effective diffusivity of the water in the grain \((D_{ef})\) with temperature is classically represented by the Arrhenius’s equation.

\[
D_{ef} = D_0 \exp(-B/T_f)\; \text{ where, } B = E/Rg
\]

(3)

where \(B = E/Rg\) and where \(D_0\) is a parameter \((m^2 \; s^{-1})\), \(T_f\) is the temperature (Kelvin) of fluid phase, \(E\) is the activation energy \((Jkg^{-1})\) and \(Rg\) is the universal gas constant \((Jkg^{-1}K^{-1})\).

The equation has two parameters \((D_0\) and \(B\)) and the parameters estimation by the least squares method demonstrated that there was a high correlation between them. Some authors, such as Mezaki & Kittrell (1967) and Draper & Smith (1981), suggest reparametrizing this equation.

The reparametrization made in this work was based on the following transformations of equation 3:

\[
D_{ef} = D_{ef}^* \exp\left(-\frac{E}{Rg}\left(\frac{1}{T_f} - \frac{1}{T}\right)\right)
\]

(4)

\[
D_{ef}^* = D_0 \exp\left(-\frac{E}{Rg}\frac{1}{T}\right)
\]

(5)

If:

\[
\exp(\beta) = D_{ef}^*
\]

(6)

\[
\exp(\gamma) = \frac{E}{Rg}
\]

(7)

\[
T' = \frac{1}{T_f} - \frac{1}{T}
\]

(8)

substituting equations 6, 7 and 8 in equation 4, equation 9 is obtained:

\[
D_{ef} = \exp(\beta) \exp(-T' \exp(\gamma))
\]

(9)

with: \(T^* = 273\) K, \(T_s\) in degrees Kelvin and \(D_{ef}\) in \(cm^2\; min^{-1}\). The parameters estimated by the least
squares method (Barrozo et al., 1994), where $\beta = 13.185$ and $\gamma = 8.36$.

The model

The following hypotheses were assumed in the development of the two-phase mathematical model:

- operation is in the steady state;
- air and solids flow is unidirectional;
- the predominant mechanism in the mass-transfer process is internal diffusion;
- grain shrinkage during the drying is negligible;
- the predominant mechanism in the heat-transfer process is convection;
- the air-velocity profile is flat;
- the flowrate of the solids is uniform;
- heat loss is negligible.

Equations 10 and 11 result from mass balance applied to the fluid and solid phases of a concurrent dryer, represented schematically in Fig. 1. Equations 12 and 13 represent the respective energy balances.

\[
G_f \frac{dW}{dx} = f_m a \quad (10)
\]
\[
G_s \frac{dM}{dx} = -f_m a \quad (11)
\]

\[
\frac{dT_f}{dx} = -\frac{ha(T_f - T_s)}{G_f(Cp_f + WCp_v)} 
\]

\[
\frac{dT_s}{dx} = \frac{ha(T_f - T_s) - f_m a(\lambda + C_p T_f - C_p T_s)}{G_s(Cp_s + MC_p)} 
\]

where $G_f$ and $G_s$ are the flowrates, per unit area, of gas and solid, respectively, $W$ is the absolute air humidity, $f_m$ is the local drying rate per unit area, and $a$ is the interfacial transfer area per bed volume unit.

Equations for the heat-transfer coefficient, equilibrium moisture and drying kinetics

The equations used for the heat-transfer coefficient, drying kinetics and equilibrium were taken from specific studies. For the heat-transfer coefficient ($h$) the following correlation by Sartori (1986) for the concurrent dryer was used:

\[ \text{Nu} = 0.84 \text{Pr}^{1/3} \text{Re}^{0.65} \]  

where $\text{Nu}$, $\text{Pr}$ and $\text{Re}$ are the Nusselt, Prandtl and Reynolds numbers, respectively.

Equation 1 was used to predict the moisture content of the grains. The drying kinetics was represented by equation 2.

Numerical solution

The initial value problem defined by equations 10–13 and the initial conditions (equation 14) was solved using the DASSL code (Petzold, 1989), which implements BDF formulas for index zero and index one general systems of differential algebraic equations in FORTRAN. This index zero model was solved for the vector of relative tolerances $\text{RTOL} = [10^{-12}, 10^{-12}, 10^{-8}, 10^{-8}]$ related

Figure 1 Schematic representation of concurrent flow-sliding bed.
to the variables $W$, $M$, $T_c$, $T_s$ and absolute tolerances $ATOL$ equal to $1 \times 10^{-6}$ using the normalized spatial variable $x' = x/L$, where $L$ is the length of the bed.

**Materials and methods**

**Materials**

The experiments were performed with soybean seeds, of the Brazilian Doko variety, with $dp = 6$ mm.

**Experimental methodology**

The schematic diagram of the experimental set-up of the concurrent moving bed is shown in Fig. 2.

The solid flow system consisted of a top hopper (Fig. 2a) at a height of 3 m, through which the seeds flowed by gravity passing through the measuring cell (Fig. 2b). At the lower reservoir, the grain flow was controlled by a conveyor belt (Fig. 2c) connected to a velocity controller (Fig. 2d). Before the measuring cell, pressure equalisers (Fig. 2e) were used to ensure concurrent flow between the grains and the drying air.

The air flow system was comprised of a blower (Fig. 2f), gate valves (Fig. 2g), an electric heater (Fig. 2h) connected to a voltage controller (Fig. 2i), an orifice plate (Fig. 2j) for the measurement of air-flow rate (uncertainty = 4.0%), screens (Fig. 2k) operating as air distributors and the measuring cell. The cylindrical shaped measuring cell had a diameter of 8 cm and a height of 64 cm. The whole unit was thermally insulated.

The air temperature was measured by copper-constantan thermocouples (ECIL Produtos e Sistemas de Medicã£o e Controle Ltda. Piedade - Sã o Paulo, Brasil) (uncertainty = 0.2 °C). Thermocouples (L) were placed at the air inlet and at nine different positions along the bed. Thermocouples in the bed were encased in small perforated cylinders to avoid their contact with the grain. The seed temperature was measured with copper-constantan thermocouples installed in small thermally insulated containers, enclosing a sample of the seeds. The samples were removed through retrieves (m) installed longitudinally in the bed. Air humidity was measured by means of psychrometers placed at the inlet and the outlet of the bed (uncertainty = 4.0%). Moisture content of the seeds was determined by drying in a regulated oven (FANEM Model 315 SE, Sã o Paulo, Brasil) (105 °C) for 24 h (uncertainty = 1.0%). The grain flowrate was periodically measured (every 5 min) by weighing the discharged grain (uncertainty = 4.0%).

**Fluid dynamics**

The measurements of the air-velocity variation in the empty cell, along the radial direction, were

![Figure 2 The experimental set-up.](image-url)
performed with an anemometer (TSI Incorporated, St Paul, MN, USA), at the air inlet, and at 9 cm and 25 cm from the inlet, for three different air-flow rates ($4.2 \times 10^{-3}$, $5.2 \times 10^{-3}$, $6.7 \times 10^{-3}$ kg/s).

The particle residence time was determined through the introduction of some coloured soybean seeds with the other beans at the bed inlet. The time taken by the coloured particles to leave the bed was measured.

**Operational conditions**

The experimental conditions were chosen taking into account the limits imposed by the quality indicators of the seeds (Barrozo et al., 1996a). An experimental design was used (Box et al., 1978) and all experiments were repeated twice.

**Results and discussion**

**Fluid dynamics results**

The variation of the air velocity in the radial direction (with the cell empty) was determined for air-flow rates of $4.2 \times 10^{-3}$ and $6.7 \times 10^{-3}$ kg s$^{-1}$, respectively.

It was observed that at the different air-flow rate levels, the air velocity varied in the radial direction at different positions in the bed, by around 3.5%. As the uncertainty in the velocity measurements with the anemometer was ± 3.0%, the profile of the inlet air velocity was effectively flat.

Figure 3 shows the residence time distribution of the particles. The results confirm the hypothesis of uniform velocity for the grains.

**Drying results**

Figures 4 and 5 show typical results of the comparison between the experimental data and the simulated responses for the moisture of the seeds.
The average deviation between the experimental and simulated for the seed’s moisture was 1.7%, close to the precision of the measurements (1.0%). Therefore, a good agreement between the simulated and experimental values is observed.

Figures 6 and 7 present the measured and simulated air and grain temperatures, respectively, for different positions along the bed. Figure 6 shows that the heat transfer occurred mainly at the inlet of the bed. The average deviation between the experimental data and simulated responses was 6.6%. Figure 7 verifies that the thermal change took place mainly in the inlet of the bed. The average deviation between the experimental and simulated values was 5.3%.

The deviations between the experimental and simulated data for air and seed temperature were higher than the uncertainty of temperature measurement (0.2 °C), mainly in the inlet region of the bed, owing to the largest temperature gradients in this region (see Figs 6 and 7). The thermocouple position on the bed and the heat loss to the surrounding contribute to increase the deviations. Furthermore, the value of the heat-transfer coefficient (h) taken from Sartori (1986) could have had a significant influence on the results.

Conclusions

The methodology presented in this work, based on the modelling of simultaneous heat and mass-transfer phenomena and on the use of specific correlations for heat-transfer coefficient, equilibrium and drying kinetics, gave model parameters which were estimated from independent studies, rather than by fitting to experimental data.

In the modelling it was assumed that the air-velocity profile is flat and that the flow rate of the grains is uniform, and this was confirmed experimentally.

The average deviations between the experimental and simulated data for air temperature, seed temperature and seed moisture were 6.6%, 5.3% and 1.7%, respectively. The fact that the closest agreement with the model was for grain moisture could be as a result of higher experimental precision of this measurement.

Nomenclature

\[ a = 6(1 - e) / \phi dp \]

interfacial transfer area per bed volume unit

\[ C_p \]
specific heat

\[ D_0 \]
parameter

\[ D_{ef} \]
effective mass diffusivity of the water inside the grain

\[ dp \]
diameter of the sphere of equal volume

\[ E \]
activation energy

\[ f_m \]
local drying rate per area unit


