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

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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

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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 & Pfost (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:

$$\bar{M}_{eq} = ((-\exp(-0.00672 * T_S + 3.02))/\ln(UR))^{1/1.508} \tag{1}$$

where $\bar{M}_{eq}$ 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.

$$MR = \frac{\bar{M} - \bar{M}_{eq}}{\bar{M}_0 - \bar{M}_{eq}} = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left[\frac{-n^2\pi^2 D_{ef}^{t}}{R^2}\right] \tag{2}$$

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.

$$D_{ef} = D_0 \exp(-B/T_f); \quad \text{where, } B = E/Rg \tag{3}$$

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 & Kittrel (1967) and Draper & Smith (1981), suggest reparametrizing this equation.

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

$$D_{ef} = D_{ef}^{*}\exp\left(-\frac{E}{R_g}\left(\frac{1}{T_f} - \frac{1}{T^*}\right)\right) \tag{4}$$

$$D_{ef}^{*} = D_0\exp\left(-\frac{E}{R_g}\frac{1}{T^*}\right) \tag{5}$$

If:

$$\exp(\beta) = D_{ef}^{*} \tag{6}$$

$$\exp(\gamma) = \frac{E}{R_g} \tag{7}$$

$$T' = \frac{1}{T_f} - \frac{1}{T^*} \tag{8}$$

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

$$D_{ef} = \exp(\beta)\exp(-T'\exp(\gamma)) \tag{9}$$

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.

$$G_f \frac{dW}{dx} = f_m a \qquad (10)$$

$$G_s \frac{d\bar{M}}{dx} = -f_m a \qquad (11)$$

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.

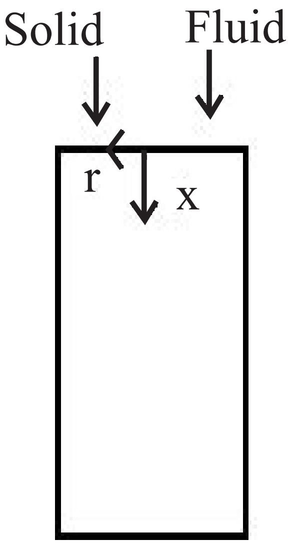

Figure 1 Schematic representation of concurrent flow-sliding bed.

$$\frac{dT_f}{dx} = -\frac{ha(T_f - T_s)}{G_f(Cp_f + WCp_v)} \qquad (12)$$

$$\frac{dT_s}{dx} = \frac{ha\ (T_f - T_s)}{G_s(Cp_s + \bar{M}Cp_l)} - \frac{f_m a(\lambda + Cp_v T_f - Cp_l T_s)}{G_s(Cp_s + \bar{M}Cp_l)} \qquad (13)$$

where h is the heat-transfer coefficient, Cp is the specific heat, and λ is the enthalpy of the water vapourization.

The initial conditions of the air humidity, seeds moisture and both air and seeds temperatures were assumed constant at the dryer inlet.

$$\begin{aligned} W(0) &= W_0 \\ \bar{M}(0) &= \bar{M}_0 \\ T_f(0) &= T_{f0} \\ T_s(0) &= T_{s0} \end{aligned} \qquad (14)$$

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:

$$Nu = 0.84 Pr^{1/3} Re^{0.65} \qquad (15)$$

where Nu, Pr and 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 $RTOL = [10^{-12}, 10^{-12}, 10^{-8}, 10^{-8}]$ related to the variables W, $\bar{M}$, T_f, T_s and absolute tolerances ATOL equal to 1×10^{-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 Medicāo e Controle Ltda. Piedade - Sāo 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, Sāo 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

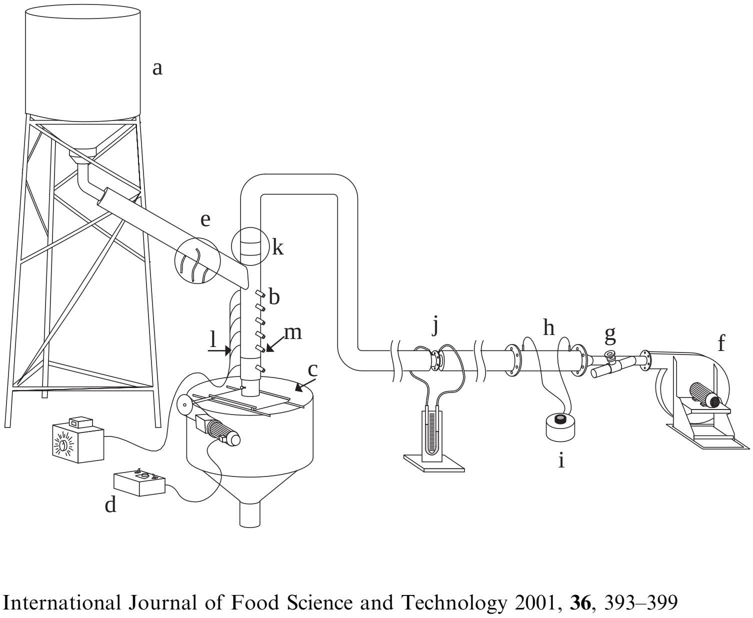

Figure 2 The experimental set-up. (a) top hopper; (b) measuring cell; (c) conveyor belt; (d) velocity controller; (e) pressure equalisers; (f) blower; (g) gate valves; (h) electric heater; (i) voltage controller; (j) orifice plate; (k) air distributor screens; (l) thermocouples; and (m) seed retrieves.

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 (4.2×10^{-3}, 5.2×10^{-3}, 6.7×10^{-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 4.2×10^{-3} and 6.7×10^{-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.

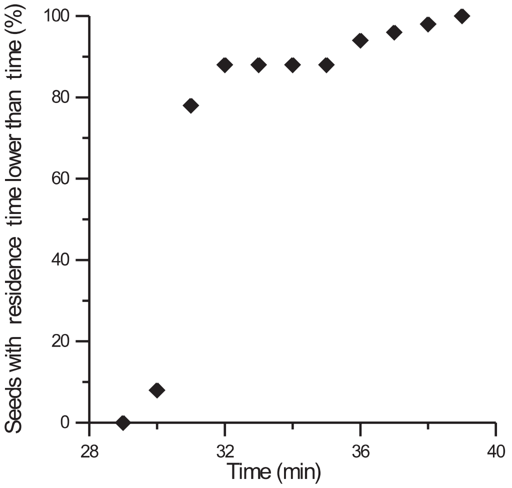

Figure 3 The air-velocity profile for flow rate of 4.2×10^{-3} kg s^{-1}.

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

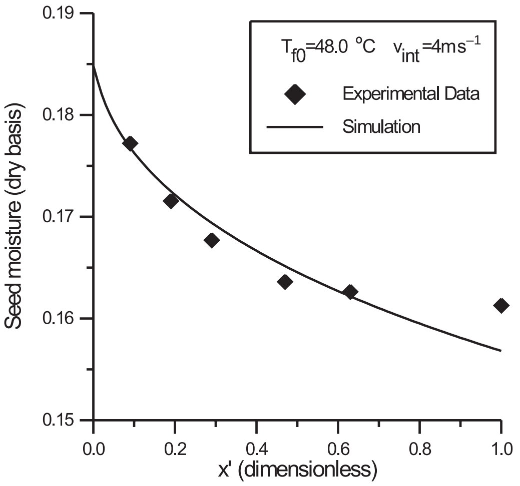

Figure 4 The air-velocity profile for flow rate of 6.7×10^{-3} kg s^{-1}.

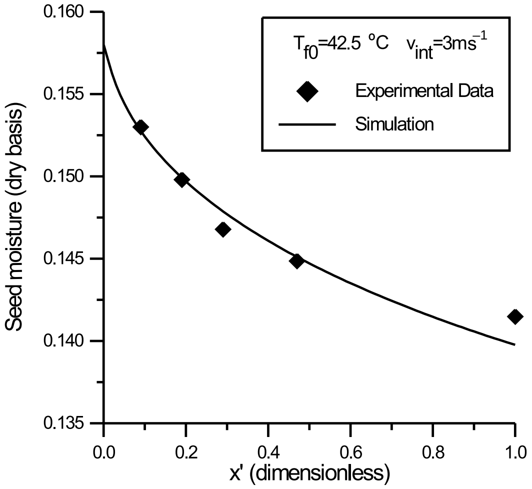

Figure 5 Residence time distribution of the particles.

seed. 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%.

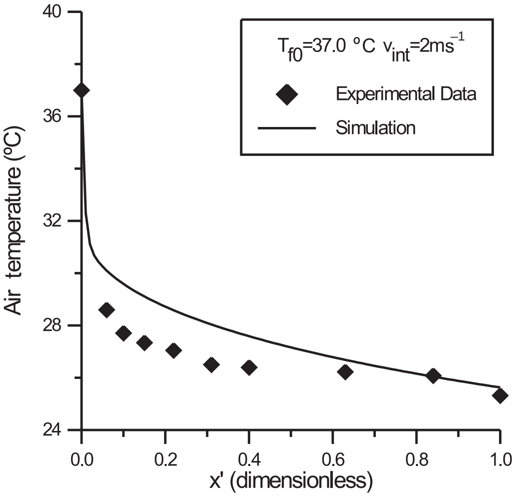

Figure 6 Experimental data and simulated profile for seed moisture, (T_{f0} = 48.0 °C; v_{int} = 4m s^{-1}).

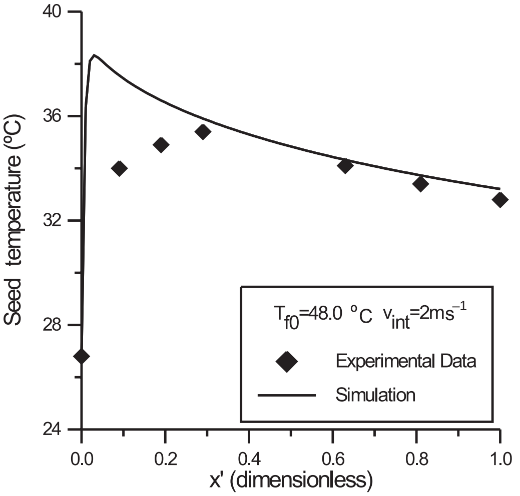

Figure 7 Experimental data and simulated profile for seed moisture, (T_{f0} = 42.5 °C; v_{int} = 3m s^{-1}).

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

$a = 6(1 - \varepsilon)/\phi dp$	interfacial transfer area per bed volume unit
Cp	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

G_f	mass flow of dry gas
G_s	mass flow of dry solid
h	heat-transfer coefficient
L	length of the bed
$\bar{M}$	average volumetric seed moisture, mass of water per mass of dry solid
MR	dimensionless moisture number
Nu	Nussellt number
Pr	Prandlt number
R	particle radius
Re	Reynolds number
R_g	universal gas constant (as applied to water vapour)
t	time variable
T	temperature
UR	relative humidity of the air
V	fluid velocity
x	co-ordinate of the grain-flow direction
x'	x/L^{-1}
W	absolute air humidity, mass of water per mass of dry air
Λ	enthalpy of the water vapourization
ε	porosity
ϕ	sphericity

Subscript

eq	equilibrium
f	fluid (air)
int	interstitial
L	liquid (water)
0	inlet conditions
s	solid (seed)
v	vapour

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