Fluidisation velocities during processing of whole soybean snack

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ABSTRACT

Soybeans contribute to healthy nutrition because of the high proportion and quality of proteins. Its oil content is considerably lower than in peanuts, restricting energy intake. Precooked samples prepared at increasing drying–toasting times (lower moisture contents) experienced shrinkage and deformation.

With the aim of determining design parameters for this process, fluid-dynamic studies of samples extracted at several times during drying–toasting allowed us to determine laminar and turbulent coefficients of the Ergun equation and the minimum fluidisation velocity (V_{mf}), at ambient temperatures. The turbulent coefficient increased for decreasing moistures and V_{mf} varied from 2.6 and 1.2 m/s over a 60 min process. As drying–toasting must be conducted at 140 °C, an increase by 20% in V_{mf} is required. Operating velocities were 50% above V_{mf} to produce uniform treatment. As the system requires a decreasing fluidisation velocity with time, an automatic control with time-varying target value should be devised to limit energy consumption and prevent solid losses.

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1. Introduction

Soybeans (*Glycine max*) are known by their high protein content (40% w/w) with good aminoacid profile, as well as by their lipid content of about 20% w/w (Deshpande et al., 1993). In soybean-producing Western countries as USA, Brazil and Argentina, grains are used at industrial level for oil extraction and the defatted residue, rich in proteins, is used domestically or exported mainly for animal feed, which is a way to improve the biological value of proteins. While some Asiatic countries appreciate the nutritional potential of whole soybean products in their diets, there is plenty of scope to introduce them in the west. For instant, in spite of being Argentina the first producer per capita of soybeans in the world, their whole grain consumption is very low because a strong culture was formed over the years towards the consumption of animal proteins (Cuniberti et al., 2004).

Raw soybean cannot be consumed directly due to the presence of "antinutritional" substances, which can affect human health. These can be inactivated by a thermal treatment. Osella et al. (1997) and Soponronnarit et al. (2001) have proposed hot air fluidisation as an inactivation process, suggesting temperatures of about 140 °C. The high air velocities required for fluidisation and the intense particle mixing (Yang, 2003) characteristic of the fluidisation of large particles, make the technique highly suitable to process value-added foods (Senadeera et al., 2006). Moreover, Giner and De Michelis (1988), in a computer simulation study of wheat drying, have found that the fluidisation process have a high potential for energy recovery.

In the last decades, the consumption of dehydrated, ready-to-eat, crispy products has increased (Aguilera et al., 2003) which justifies the development of a process by which soybean is precooked and inactivated and then dried and toasted by fluidised bed to form a porous structure.

However, no studies on the hot air fluidisation of precooked soybeans were found in the literature, so that a research was decided to characterise the process parameters, particularly the range of fluidisation velocities required.

In a previous work aimed at studying density and volume of whole precooked soybean during hot air fluidisation, particles were observed to shrink during the process and, at the same time, become less dense (more porous), so the required fluidisation parameters may change with time (Torrez-Irigoyen and Giner, 2011). The objectives of this work were (1) to determine variations in the minimum fluidisation velocity (V_{mf}) of soaked–cooked, and partially and totally dried toasted samples produced by fluidisation in air at 140 °C and (2) to evaluate the influence of air temperature on the value of V_{mf}.

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Notation

A_p	surface area of particle, m^2
D	diameter of fluidisation chamber, m
D_e	equivalent diameter of particle, m
D_p	effective diameter of particle, m
f_c	Coulson factor for wall effect, dimensionless
g	average acceleration of gravity, 9.81 m s^{-2}
K_1	laminar coefficient in Ergun equation
K_2	turbulent coefficient in Ergun equation
L_{mf}	height of fluidised bed at the minimum fluidisation velocity, m
L_0	fixed bed height, m
l_1	longest axis of soybean grains, mm
l_2	intermediate axis of soybean grains, mm
l_3	shortest axis of soybean grains, mm
l_m	average of l_2 and l_3, mm
p	absolute pressure at sea level, 1.01325×10^5 Pa
M_a	molar mass of air, kg kmol^{-1}
R	gas constant, 8314 J kmol^{-1} K^{-1}
S	cross sectional area, m^2

T_C	temperature, °C
T_K	absolute temperature, K
V_0	air superficial velocity, m s^{-1}
V_p	particle volume, m^3
V_{mf}	minimum fluidisation velocity, m s^{-1}
V_f	operating fluidisation velocity, m s^{-1}
W	soybean moisture content, kg water/kg dry matter

Greek symbols

π	constant
ρ_a	fluid density, kg m^{-3}
ρ_{B0}	fixed bed density, kg m^{-3}
ρ_p	particle density, kg m^{-3}
Δp	static pressure drop across the bed, Pa
ε_0	fixed bed void fraction, dimensionless
μ_a	air viscosity, kg m^{-1} s^{-1}
ψ	sphericity factor, dimensionless

2. Materials and methods

2.1. Material

Soybeans variety Don Mario 5.5 i were kindly provided by Don Mario Semillas (Don Mario Seeds Company), Chacabuco, Provincia de Buenos Aires, Argentina (http://www.donmario.com).

2.2. Determination of moisture content

Moisture content was measured by an oilseed-specific whole grain method at atmospheric pressure (AOCS Ac 2-41, 130 °C for 3 h). With this purpose, an automatically-controlled mechanical convection oven (average air velocity, 0.25 m/s), was utilised. Moisture content was expressed in kg water/kg dry matter, units that are often referred to as "decimal dry basis", or dec., d.b. Moisture content of the sample at reception was 0.113 dec., d.b.

2.3. Preliminary operations

Grains at reception were visually inspected to remove any foreign material. They were then washed by immersion in hot water (90 °C) for 1 min, two times. Subsequent treatments were carried out according to the experimental plan shown in Fig. 1, and described next.

2.4. Soaking and cooking of soybean grains

The washed samples were immersed in water (water-to-soybean mass ratio of 2:1) for 24 h at 10 °C, then drained and immersed in boiling water for 45 min for the cooking stage (Torrez-Irigoyen and Giner, 2011).

2.5. Surface drying

As the seedcoat of cooked and drained grains remains wet, this condition would difficult fluidisation of samples during drying–toasting. For this reason, grains were surface-dried by distributing them in a thin layer one grain deep on a tray, and placed in the mechanical convection oven described above (Section 2.2) for 10 min at 50 °C.
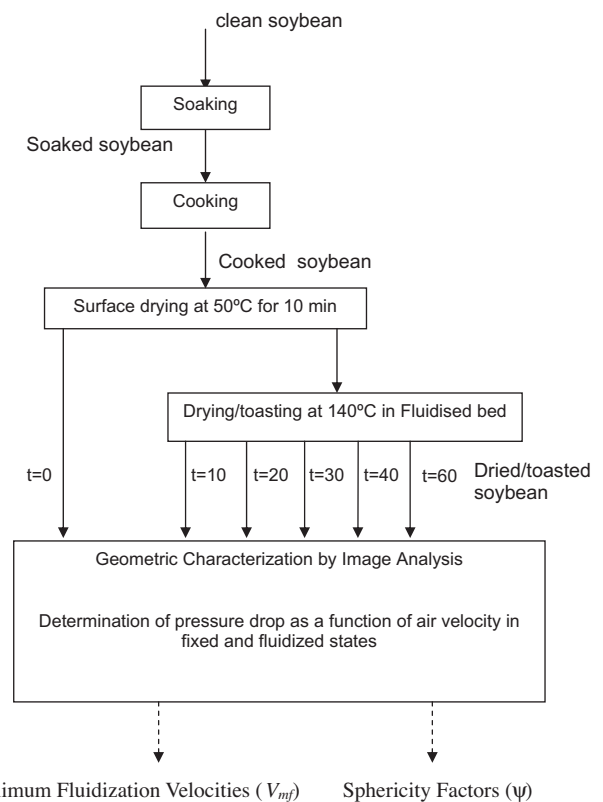

Fig. 1. Flowsheet representing the experimental plan carried out. Information flow (- - -) and materials flow (–).

2.6. Fluidised-bed equipment

Fig. 2 is a schematic of the purpose-built experimental fluidised-bed dryer. It consists of five main components: (A) drying chamber, 0.10 m internal diameter and 0.30 m in height, (B) a Testo 525 micromanometer (measuring range: 0–25 hPa, error: 0.2% of full scale) to measure differences in air pressure across the bed, (C) a TSI Mod. 1650 hot wire anemometer, to measure the superficial air velocity, (D) a Novus Brand Model N321-J/Kit Temperature Controller, with a measuring range from 0 to 600 °C and
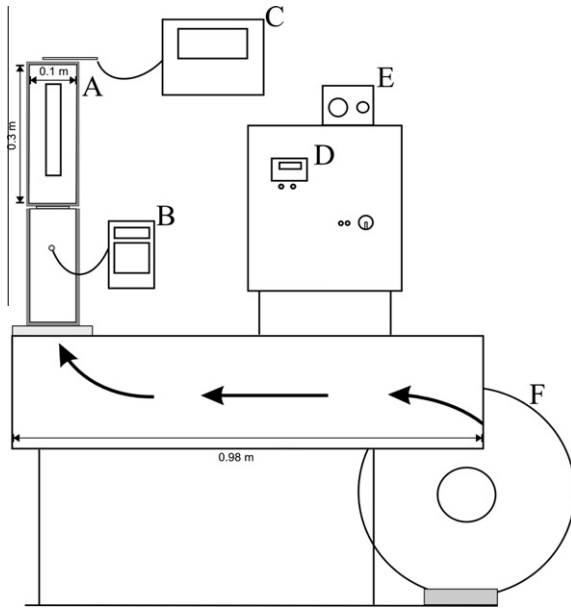
Fig. 2. (A) Drying chamber, (B) TESTO 525 Micromanometer, (C) TSI Mod. 1650 hot wire anemometer, (D) temperature controller, (E) angular speed controller and (F) centrifugal fan.

an accuracy of ±0.5 °C, (E) angular speed controller, a system which modifies the frequency of the alternating current, and (F) a centrifugal fan, directly connected to a Siemens electric motor with a maximum angular speed of 2800 rev/min.

2.7. Determination of fixed bed density and void fraction

Fixed bed density was measured in the drying chamber with the samples prepared as described in Fig. 1. Each sample (500–550 g) was weighed in 1500 g capacity OHAUS precision balance (readability, 0.01 g) and loaded to the drying chamber. In order to standardise bed packing, the fan was switched on, to bring the sample to a fluidised condition, and was then switched off, to recover the fixed bed condition again. Minor sample mass adjustments were made to attain a fixed bed height of 0.10 m. The fixed bed density (ρ_{B0}) was calculated by dividing the sample mass by the bed volume, formed by the volume of particles (understood as envelope volume) plus that of voids.

On the other hand, for each sample, the ratio of the fixed bed density to the particle density provides the fraction of the bed occupied by the solids. Therefore, the fixed bed void fraction (ε_0) was calculated by the following equation.

$$\varepsilon_0 = 1 - \frac{\rho_{B0}}{\rho_P} \tag{1}$$

where ρ_P is the particle density.

2.8. Drying–toasting in fluidised bed

The drying–toasting process was carried out in hot air set at 140 °C in the fluidised bed equipment described in Section 2.6. To avoid excessively intense fluidisation and possible sample losses by undesired pneumatic conveying, the air velocity was manually decreased from 3.5 m/s at $t = 0$ to 1.7 m/s, the latter value being maintained between $t = 40$ and $t = 60$ min. Velocities were enough to maintain a high degree of mixing and thus uniform thermal treatment. Fixed bed height was 0.10 m. All experiments were conducted in triplicate. Samples were produced by drying–toasting them for different times, from 0 to 60 min. Each of the samples was allowed to rest in hermetic containers at 10 °C for 24 h to ensure a

uniform moisture distribution. This was considered important to evaluate equilibrium pycnometric volume and density of soybeans, which were reported in a previous work (Torrez-Irigoyen and Giner, 2011).

3. Geometric characterisation by image analysis

An existing Matlab program (Goñi and Purlis, 2010) was modified to calculate the major axes of soybeans for the different samples, using digital photographs. The pictures were taken with a Kodak M753 digital camera, using a resolution of 2292 × 3056 pixels. Two photographs of each sample (20 grains) were taken, one with grains being observed in plan view and another in front view. The Matlab program reads the image in JPG format along with a conversion factor to transform pixels in milimeters. As an intermediate result of the program, a histogram of intensities is exhibited after which a datum must be manually input to adjust image contrast. The program then generates a binary image with soybeans in white and background in black, which allows an automatic calculation of the two major axes in each image. As suggested by Goñi and Purlis (2010), the background and the lighting must be properly selected to enhance the contrast and ensure good segmentation.

By choosing an ellipsoidal geometry for the soybeans, the following formula was employed, using the grain three major axes as data, to calculate the grain surface area (Gastón et al., 2002):

$$A_P = \frac{\pi}{2} l_1 l_m \left[\frac{l_m}{l_1} + \frac{1}{E} sin^{-1} E \right] \tag{2}$$

where

$$E = \frac{(l_1^2 - l_m^2)^{1/2}}{l_1} \tag{3}$$

Symbol l_1 is the longest axis, being l_m the average of the intermediate (l_2) and shortest (l_3) axis, in mm.

The sphericity factor ψ, defined as the ratio of the surface area of a sphere with equal volume as the particle to the surface area of the particle (Senadeera et al., 2006), is calculated by

$$\psi = \frac{\pi D_e^2}{A_P} \tag{4}$$

where D_e is the equivalent diameter of soybeans, calculated from the pycnometric data measured in a previous work (Torrez-Irigoyen and Giner, 2011).

The effective diameter (D_p) or diameter of a sphere with the same surface-to-volume ratio as the particle (Tosi et al., 1988), was calculated by

$$D_P = \psi D_e \tag{5}$$

The values of D_p are relevant as characteristic particle dimensions for fluid-dynamics studies of fixed beds (Ergun, 1952).

3.1. Statistical analysis

Triplicate experiments were conducted for each drying toasting fluidisation time, measuring particle diameter as a function of the moisture content at that time. Differences between the geometric parameters among the various samples were evaluated by the Tukey's test (Montgomery, 1991), at a confidence level of 95%.

4. Study of the fluid dynamics in fixed and fluidised bed conditions

The fluid dynamic characteristics of samples prepared by cooking plus drying–toasting periods from 0 to 60 min, were experi-

mentally studied to determine the minimum fluidisation velocities (V_{mf}). This procedure was carried out at 20 °C by measuring the air pressure drop through the bed as a function of the superficial air velocity in a range comprising the fixed bed zone, the transition zone between fixed and fluidised states, and the fluidised bed region, as described in Section 2.6. The Ergun (1952) expression (Eq. (7)) was fitted to the fixed bed data in order to determine their two parameters (K_1 and K_2). In turn, the value of V_{mf} was found by a mathematical procedure using information from fixed and fluidised states, described in the next section.

4.1. Determination of parameters of the Ergun equation

For each of the various samples utilised, measured data of air pressure drop per unit bed height ($\Delta p / L_0$) were plotted as a function of the measured superficial air velocity (V_0). The latter, in the fixed bed region, was corrected by multiplying it by f_c, defined as the Coulson factor. This takes into account possible wall effects caused by looser bed packing near the chamber walls (Coulson and Richardson, 2000).

$$f_c = \frac{1}{\left[1 + \frac{\left(\frac{4}{D}\right)}{2\left(\frac{6}{D_e}\right)}\right]^2} \tag{6}$$

where D stands for dryer chamber diameter. The value of f_c was 0.95 for soaked–cooked soybean, and 0.96 for the totally dried–toasted product. Therefore, wall effects are considered low.

The Ergun type equation (Ergun, 1952) was fitted to the experimental data of the fixed bed zone:

$$\frac{\Delta p}{L_0(1 - \varepsilon_0)} = K_1 \frac{(1 - \varepsilon_0)\mu_a}{D_P^2 \varepsilon_0^3} V_0 + K_2 \frac{\rho_a}{D_P \varepsilon_0^3} V_0^2 \tag{7}$$

where μ_a is the air viscosity in kg/m s, ρ_a air density, kg/m³. By investigating the fluid-dynamic characteristics of small particles of inorganic origin, Ergun (1952) found the coefficients of the laminar and turbulent terms K_1 and K_2 to be 150 and 1.75, respectively. However, these values actually depend on product characteristics (Delele et al., 2008), especially in large particles, and must be determined by fitting with experimental data. In order to properly select the data of the fixed bed region, Eq. (7) was first expressed as a straight line (Escardino et al., 1974) dividing its both members by V_0

$$\frac{\Delta p}{L_0(1 - \varepsilon_0)V_0} = K_1 \frac{(1 - \varepsilon_0)\mu_a}{D_P^2 \varepsilon_0^3} + K_2 \frac{\rho_a}{D_P \varepsilon_0^3} V_0 \tag{8}$$

Therefore, by rearranging experimental data as the left member of Eq. (8) and representing them as a function of V_0, fixed bed behaviour should be represented by a linear trend (Fig. 5). However, once the "pure" fixed bed data was separated and in view that the parabolic form (Eq. (7)) usually provides more accurate fitting parameters than the linear version (Eq. (8)), the former (Eq. (7)) was chosen for fitting to the data, using a statistical computer software (Systat, 1990).

4.2. Determination of V_{mf}

The minimum fluidisation velocity (V_{mf}) is reached as the fluid pressure drop through the bed multiplied by the cross section equals product weight in the fluid. The latter is obtained from the difference between product weight and the buoyancy force in the fluid (Werther, 1999). As the cross sectional area appears in both members of the equation, it can be cancelled out and the remaining mathematical expression becomes

$$\Delta p = (\rho_P - \rho_a)g(1 - \varepsilon_{mf})L_{mf} \tag{9}$$

L_{mf} and ε_{mf} are the bed height and void fraction at $V_0 = V_{mf}$, while g is the acceleration of gravity. However, as the mass of solids remain constant in fixed and fluidised states, the following expression holds true

$$(1 - \varepsilon_{mf})L_{mf} = (1 - \varepsilon_0)L_0 \tag{10}$$

Therefore, Eq. (10) was replaced into Eq. (9) to obtain

$$\frac{\Delta p}{L_0(1 - \varepsilon_0)} = (\rho_P - \rho_a)g \tag{11}$$

The left member of Eq. (11) can be replaced by the right member of Eq. (7), evaluated at V_{mf}. This is possible because, nominally, the V_{mf} belongs both to fixed bed and fluidised bed conditions

$$K_2 \frac{\rho_a}{D_P \varepsilon_0^3} V_{mf}^2 + K_1 \frac{(1 - \varepsilon_0)\mu_a}{D_P^2 \varepsilon_0^3} V_{mf} - (\rho_P - \rho_a)g = 0 \tag{12}$$

where V_{mf} is the solution with physical meaning of Eq. (12). The approximation $\varepsilon_{mf} \approx \varepsilon_0$ was utilised, because determination of ε_{mf} is cumbersome during fluidisation of large particles, and the procedure may not provide a value significantly different from ε_0 (Formisani et al., 1998).

5. Results and discussion

5.1. Geometric characterisation of soybean grains

Fig. 3 shows an example of the image analysis processing for sample DT 20 (dried–toasted for 20 min). The program reads the photograph of soybean grains to produce an intermediate result, a binary black and white image where grains appear in white. The program then proceeds by calculating the main axis. Fig. 4
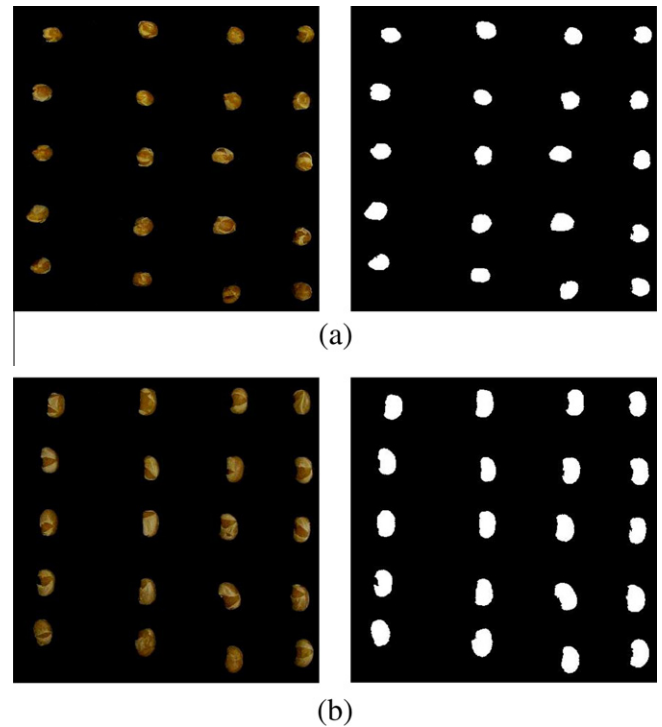

(a)

(b)

Fig. 3. (a, left) shows a colour digital photograph of grains in front view. This image is read by a Matlab program to produce a binary file (black: background; white: grains) shown at the right of figure (a), which is utilised to determine grain dimensions. A similar explanation, though for a plan view, can be offered for figure (b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
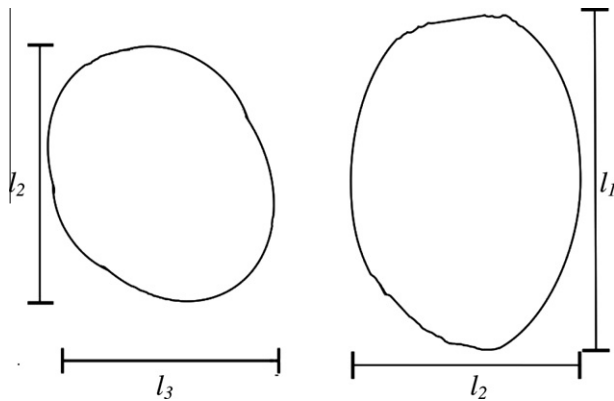
Fig. 4. Drawing of front view and plan view of the grain and their axis l_1, l_2 and l_3 measured by image analysis and utilised to calculate grain surface area and sphericity.

shows a drawing of front and plan view of soybean grain, which specifies the axis taken to perform the calculations.

For soaked–cooked soybean samples, dried toasted for 10–60 min, i.e. differing each other in moisture content, grain volume, shape and density, Table 1 shows the values of the main axes, surface area, sphericity factor and equivalent spherical diameter. The effective diameter, also listed in Table 1 and calculated using Eq. (5), is possibly the most relevant value because it is employed in the Ergun equation. The sphericity factor gradually decreases during drying toasting from 0.96 to 0.94 as the particles change from their initial "beany shape", to a more irregular contour after shrinkage and deformation.

As moisture contents decreases, grain axes also reduce considerably. Comparing soaked cooked (CS) and totally dried–toasted (DT 60) samples, values of D_e and A_p decreased by 18.2% and 27.4% respectively. The Tukey's test confirmed that the geometric dimensions of samples CS and DT 60 differed significantly ($p < 0.05$).

These differences indicate the presence of changes in product structure during drying toasting. Aguilera (2003), by studying products under the microscope, has suggested that most foods dried to low moisture content experience structural changes. Lewicki (2006) has also found structural modifications in products during dehydration.

5.2. Fluid dynamic study of fixed and fluidised beds of soybean samples

5.2.1. Determination of Ergun parameters

According to the experimental plan outlined in Fig. 1, a fluid-dynamic study was carried out on soaked–cooked samples as well as on those dried–toasted for several times.

Table 1
Geometric parameters of whole soybeans at different moisture contents during fluidised bed drying–toasting. The first row of the table presents the values for raw soybean.

W (kg water/ kg dry matter)	l_1 (mm)	l_2 (mm)	l_3 (mm)	A_p (mm²)	ψ (dimensionless)	D_e (mm)	D_p (mm)
Drying/toasting at 140 °C							
0.113	6.93	6.25	5.51	121.9	0.99	6.321	6.258
1.494	10.67	7.34	6.85	207.4	0.96	8.288	7.956
0.711	10.32	6.66	5.48	172.6	0.95	7.140	6.783
0.273	10.49	6.63	5.38	172.5	0.94	7.127	6.699
0.102	10.18	6.53	5.29	165.4	0.95	6.982	6.633
0.056	9.85	6.29	5.33	157.9	0.94	6.906	6.492
0.026	9.83	6.32	4.88	150.6	0.94	6.778	6.371

In Fig. 5, the pressure drops per unit bed height were plotted as a function of superficial air velocity for soaked cooked and totally dried toasted samples at 140 °C for 60 min. Partially dried toasted samples (for times greater than 0 and less than 60 min) exhibited intermediate fluid-dynamic behaviours and were not included in Fig. 5 for the sake of clarity.

In the fixed bed region of Fig. 5 and at the same value of V_0, the pressure drop in sample DT 60 was higher than in sample CS. The main cause, according to the Ergun model (Eq. (7)), would be the smaller effective diameter of the DT 60 sample (Table 1).

At large velocities, in the fluidised bed region, the pressure drops (which are defined by product weight), tend to decrease. This may be caused by some losses of light material as broken seedcoats as a consequence of undesired pneumatic conveying.

At low velocities, there is a characteristic fixed bed behaviour, with an increasing slope and concave shape of the curve. At higher velocities, the slope decreases (transitional behaviour) and, for even higher velocities it tends to the horizontal (fluidised bed behaviour). However, data of Fig. 5 do not allow a precise separation of fixed bed data from those of the transitional region.

The fixed bed zone in each sample was determined by arranging the experimental data as of $\Delta p / [(1 - \varepsilon_0) L_0 V_0)]$ as a function of V_0 (see Section 4.1), which is exhibited in Fig. 6 for sample dried–toasted for 20 min (DT 20). Fixed bed behaviour is considered valid
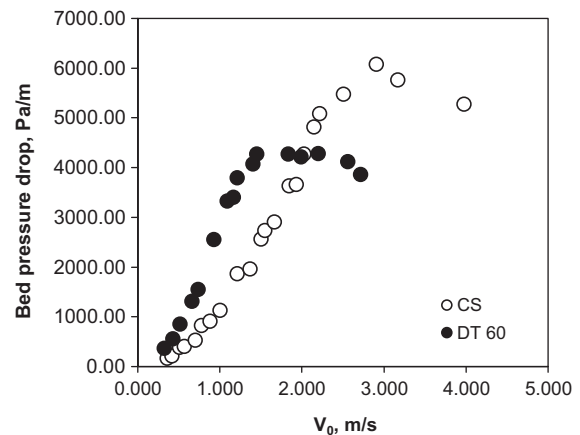

Fig. 5. Values of pressure drop per unit bed height as a function of superficial air velocity, for soaked–cooked soybeans (○) and dried–toasted soybean (●) for 60 min.
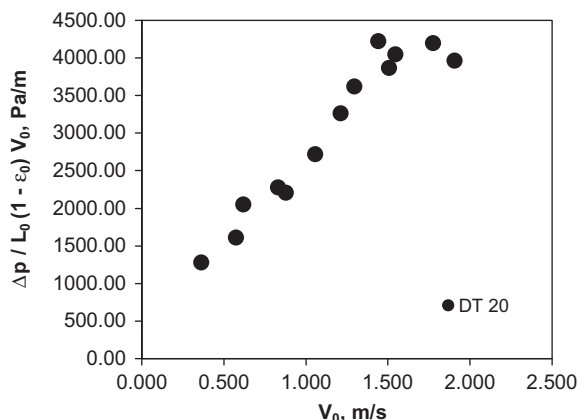

Fig. 6. Behaviour of experimental data, as the ordinate is arranged according to Eq. (8). A linear trend identifies fixed bed zone. The graph correspond to a sample dried–toasted for 20 min.

for this sample up to $V_0 = 1.5$ m/s, value above which the behaviour becomes irregular (transitional). The fixed bed regions for all samples were delimited by this procedure and are listed in Table 3.

However, once selected, fixed bed data were utilised as $\Delta p/(L_0(1 - \varepsilon_0))$ as a function of V_0 and the Ergun model (Eq. (7)) was fitted to them, using bed void fractions and effective diameters of Table 2. The results of the fitting, obtained by the nonlinear least squares method were parameters K_1 (laminar coefficient) and K_2 (turbulent coefficient). Table 3 exhibits these parameters along with their asymptotic standard errors (ASE) and the corrected coefficients of determination (r^2).

As mentioned in Section 4.1, values of laminar and turbulent coefficient depend on product characteristics, mainly surface rugosity. In this regard, Escardino et al. (1974) have worked with various cereals as rough rice, white rice, wheat, barley and maize to obtain K_1 and K_2 by fitting. They reported values from 242 to 867 for K_1 and from 3.17 to 6.54 for K_2, which are higher than those obtained by Ergun in 1952 (150 and 1.75). They attributed the differences to the rugosity of cereal surface and, besides, to bed anisotropy, characteristic of beds formed by irregularly-shaped particles. In turn, concerning the values obtained in the present work (Table 3), the laminar coefficient was determined with high error due to the high air velocities utilised in this research, so that its irregular change between the samples would not be relevant. In turn, the turbulent coefficient is particularly lower than the corresponding Ergun parameter in the soaked–cooked sample, possibly due to the smoothness of the soybean seedcoat. However, dried toasted samples experienced shrinkage, deformation, seedcoat breakage and partial loss, thus developing an irregular contour, so coefficient K_2 tends to increase. The variations in bed void fraction (Table 2), depend on bed and particle density, which turn vary with moisture content.

In Fig. 7, the experimental pressure drops (symbols) and the corresponding predicted lines were plotted as a function of superficial air velocity, using the parameters of Table 3. Agreement is satisfactory for all samples (CS, DT 10, DT 20, DT 30, DT 40 and DT 60).

Table 2
Fixed bed properties determined samples prepared by fluidised-bed drying toasting (DT) at various times (includes the initial sample of soaked–cooked soybean (CS)).

Sample	W (kg water/kg dry matter)	ρ_p (kg/m³)	ρ_{B0} (kg/m³)	ε_0
CS	1.494	1069	680.6	0.36
DT 10	0.711	909	559.5	0.38
DT 20	0.273	760	509.7	0.33
DT 30	0.102	743	427.9	0.42
DT 40	0.056	743	453.9	0.39
DT 60	0.026	750	437.2	0.42

Table 3
Parameters determined by fitting the Ergun equation (Eq. (7)) to experimental data of pressure drop vs. superficial air velocity in the fixed bed zone. Between parentheses the asymptotic standard errors (ASE) of K_1 and K_2 are indicated.

Sample	Velocity range of fixed-bed behaviour	K_1	K_2	r^2
CS	0.36–1.85	86.88 (33.99)	0.46 (0.028)	0.994
DT 10	0.36–1.36	260.46 (41.86)	0.60 (0.051)	0.994
DT 20	0.36–1.55	22.11 (38.17)	0.52 (0.044)	0.990
DT 30	0.28–1.18	234.32 (202.55)	1.64 (0.270)	0.975
DT 40	0.19–1.24	307.55 (65.97)	1.15 (0.091)	0.994
DT 60	0.33–1.09	118.64 (46.83)	1.75 (0.074)	0.998

5.2.2. Determination of the operating fluidisation velocity

Moisture content of samples was plotted as a function of time during drying toasting in Fig. 8. The value at $t = 0$ corresponds to the soaked cooked sample. A simple exponential equation was fitted to the data by nonlinear least squares, giving

$$W = 1.504 \exp(-0.081t) \tag{13}$$

where W is the moisture content (dec., d.b.) at time t in min. The coefficient of determination reveals an accurate fitting, $r^2 = 0.999$. Soponronnarit et al. (2001), which investigated drying/inactivation of raw soybean in fluidised beds, have also used a simple exponential to empirically model the experimental data of bed moisture content as a function of time.

Fig. 9 shows that the minimum fluidisation velocity, determined with Eq. (12), decreases with moisture content. For instance the value of V_{mf} for sample DT 60 is slightly less than half the value for sample CS. Therefore, lower fluidisation velocities are required with the progress of drying–toasting. If air velocity is left uncontrolled, it would naturally increase due to the decreasing weight (decreasing pressure drop) of a bed undergoing drying. This would increase energy expenditure at constant inlet air temperature will possibly cause undesired pneumatic conveying of lighter material away from the bed.

Using available data obtained in the present work, the minimum fluidisation velocity was related with soybean moisture content. Senadeera et al. (2006) and DiMattia et al. (1996) have also found a relationship between V_{mf} and moisture content, linking the variables with a linear expression. In the present work (Fig. 9), the experimental values of V_{mf} (i.e., those determined with Eq. (12)) were interpreted with an exponential empirical equation (Eq. (15)), with an r^2 of 0.983

$$V_{mf} = 1.437 \exp(-0.0638t) + 1.159 \tag{14}$$

In turn, the corresponding correlation between V_{mf} and time, which can be useful for process automation,

$$V_f = 2.649(1 - \exp(-0.490W)) + 1.189 \tag{15}$$

showed an excellent agreement with the data ($r^2 = 0.999$).

In Fig. 10, the experimental values of V_{mf} were plotted as a function of moisture content together with predictions by Eq. (14). However, fluidisation of large particles as soybean requires the use of operating fluidisation velocities (V_f) higher than V_{mf} in order to provide an adequate degree of mixing and thus a uniform thermal treatment. The excess ($V_f - V_{mf}$) traverses through the bed in the form of bubbles (Kunii and Levenspiel, 1997) which explode at the bed surface, causing intense mixing. The value of V_f is usually found as a compromise between the goal of achieving a uniform thermal treatment and the goal of reducing energy expenditure. Soponronnarit et al. (2001) and Srinivasakannan and Balasubramanian (2009) have used values of V_f of $1.5V_{mf}$ and $2V_{mf}$, respectively. In our system, a factor of 1.5 was satisfactory. The values of V_f thus obtained were also plotted in Fig. 10 as a function of time. This information can be valuable for installing an automatic velocity control of the process where the target value should be decreased with time.

5.2.3. Effect of air temperature on the minimum fluidisation velocity

In this section, a study was conducted to find out how the fluidisation parameters obtained in fluid-dynamic studies carried out at ambient temperatures can be employed in processes occurring at higher temperatures. With this purpose, air density ρ_a and air viscosity μ_a were expressed as a function of temperature in Eq. (12).
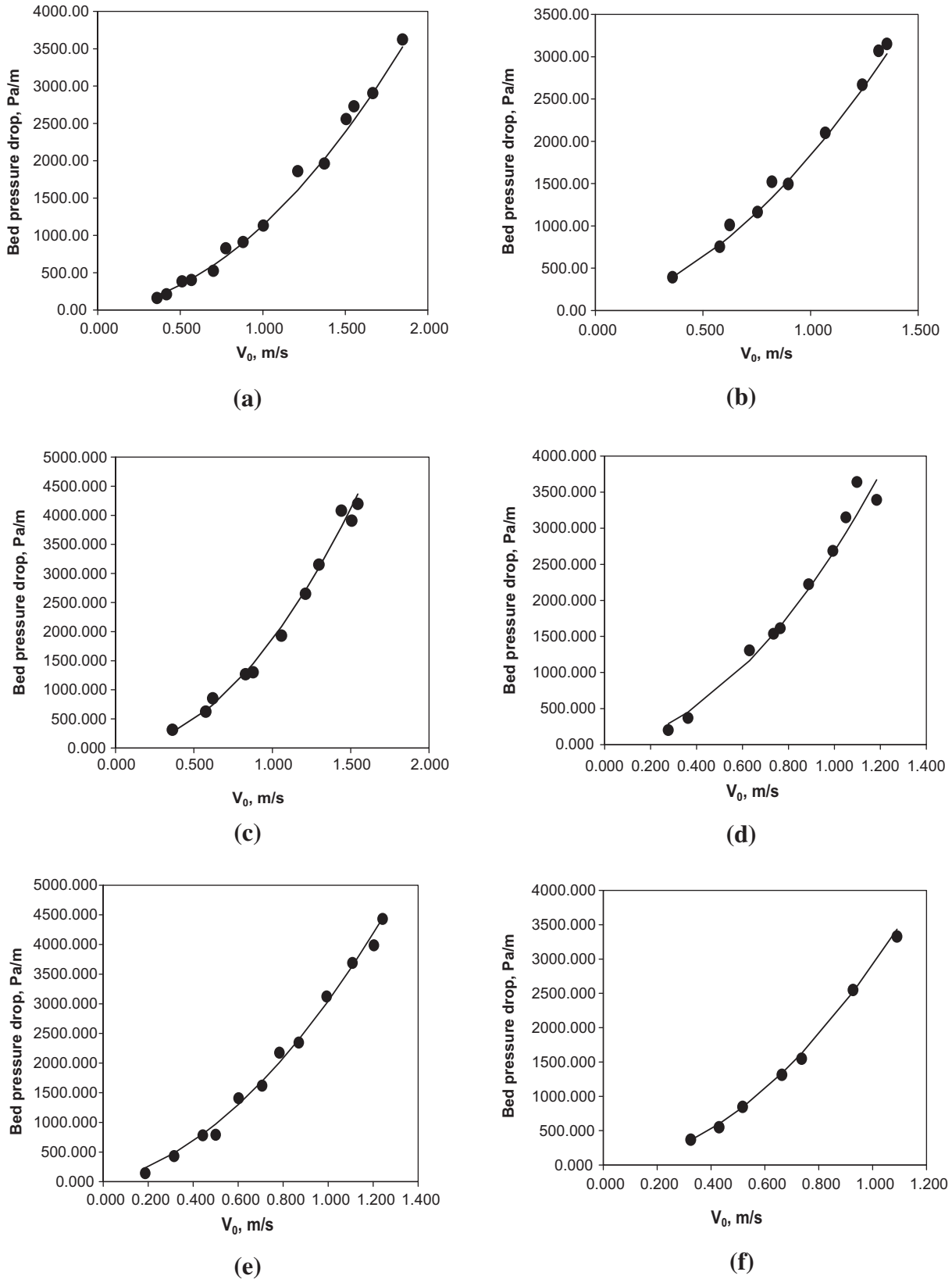
$$\rho_a = \frac{pM_a}{RT_k} \tag{16}$$

Fig. 7. Bed pressure drop per unit bed height as a function of superficial air velocity. Experimental (●) and Ergun–predicted values (–): (a) cooked soybeans (CS), (b) dried–toasted for 10 min (c) dried–toasted for 20 min, (d) dried–toasted for 30 min, (e) dried–toasted for 40 min and (f) dried–toasted for 60 min.

$$\mu_a = 1.735 \times 10^{-5} + 4.318 \times 10^{-8} T_C \qquad (17)$$

where p is the absolute pressure in Pa, M_a the molar mass of air, 28.84 kg/kmol, R the gas constant, 8314 J/kmol K and T_k the abso-

lute air temperature in Kelvin. In turn, T_C is the air temperature in °C. Considering that increasing temperatures cause a decrease in air density and increases air viscosity, the net temperature effect on V_{mf} is not obvious in Eq. (12). For that reason, Eqs. (16) and
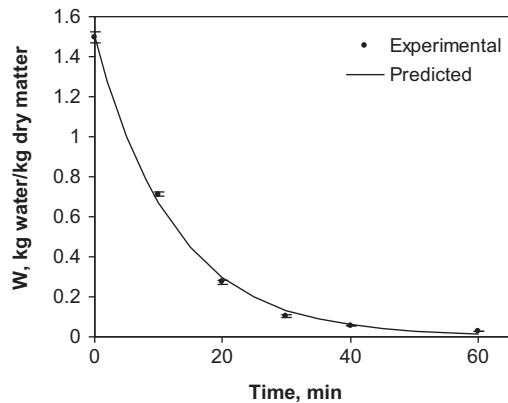
Fig. 8. Moisture content of soybean as a function of time during fluidised-bed drying–toasting at 140 °C. Experimental values (•) the empirical model-predicted line (–) shows good agreement with the data.
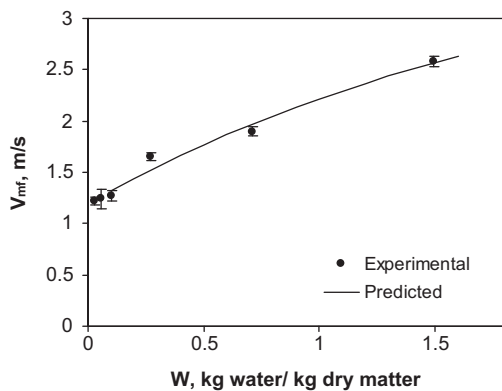

Fig. 9. Minimum fluidisation velocities of samples treated by drying–toasting for several times as a function of their corresponding moisture contents. Values determined by Eq. (12) (•). An empirical correlation (–) provides a good description for practical purposes.
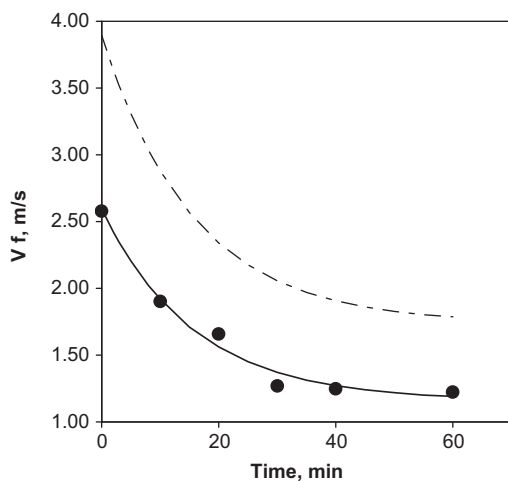

Fig. 10. Experimental minimum fluidisation velocities at 20 °C (•) at various times, along with values predicted by an empirical correlation (–). The upper curve (...) represents the operating fluidisation velocity as a function of time.

(17) were replaced in Eq. (12) and the resulting minimum fluidisation velocities were plotted in Fig. 11 as a function of air temperature in the range of 20–160 °C. At the latter temperature, the minimum fluidisation velocity for soaked–cooked soybean was 3.05 m/s, about 20% higher than its value at 20 °C. Considering that
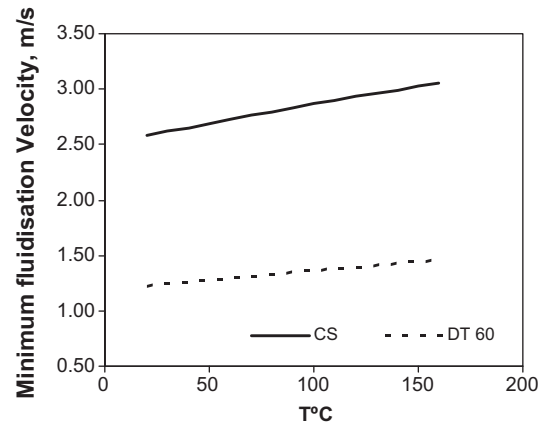

Fig. 11. Temperature effect on minimum fluidisation velocity for samples soaked–cooked soybean (–), and dried–toasted for 60 min (- - -).

the turbulent term is more important close to V_{mf}, the decrease in density ocurring as the air temperature increases will require an increase of V_{mf} in order to compensate and reach the same pressure drop to support equal bed weight. This effect must be taken into account to correct values of V_f calculated for 20 °C in Fig. 10.

6. Conclusions

Samples prepared at increasing drying–toasting times exhibited lower moisture content, lower particle diameter, a trend towards a lower fixed bed density and to a higher fixed bed void fraction. Besides the turbulent parameter of the Ergun-type equation also tends to increase, possibly reflecting a higher particle rugosity.

The minimum fluidisation velocity varied from 2.6 and 1.2 m/s during the 60 min of the drying–toasting stage. This values should be increased by 50% to attain operating fluidisation velocities that reduce from 3.9 to 1.8 m/s over the process.

The drying toasting process should be automatically controlled, in view that the system requires a decreasing fluidisation velocity with time, while the fan will naturally provide a higher velocity which, at constant temperature, will lead to excessive energy consumption and possible material losses by undesired pneumatic conveying.

The minimum fluidisation velocity increases by about 20% between 20 and 160 °C, mostly due to the decrease in air density. This effect should be considered in view that the process suggested in this work is carried out at 140 °C. Therefore, by considering the additional increase of V_{mf} caused by the effect of temperature, the practical fluidisation velocities required by the process will decrease between 4.7 and 2.2 m/s.

Acknowledgements

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