Journal of Food Engineering 171 (2016) 78–86

Contents lists available at ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

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

Ricardo M. Torrez Irigoyen [a, b], Sergio A. Giner [a, b, c, *]

[a] *Centro de Investigación y Desarrollo en Criotecnología de Alimentos (CIDCA), Facultad de Ciencias Exactas, Universidad Nacional de La Plata, Calle 47 y 116, 1900, La Plata, Provincia de Buenos Aires, Argentina*
[b] *Facultad de Ingeniería, Universidad Nacional de La Plata, Argentina*
[c] *Comisión de Investigaciones Científicas de la Provincia de Buenos Aires, Argentina*

ARTICLE INFO

Article history:
Received 16 July 2015
Received in revised form
5 October 2015
Accepted 6 October 2015
Available online 14 October 2015

Keywords:
Soybean
Drying–toasting
Fluidised-bed
Mathematical model
Simulation

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,

---

[*] Corresponding author. 47 y 116, 1900, La Plata, Argentina.
E-mail address: saginer@ing.unlp.edu.ar (S.A. Giner).

http://dx.doi.org/10.1016/j.jfoodeng.2015.10.011
0260-8774/© 2015 Elsevier Ltd. All rights reserved.

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

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

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:

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

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

Table 1
Parameters of the model.

Model	Relationships	Source
Mathematical model for volume shrinkage	$\frac{V}{V_0} = 1 - a\frac{\rho_0(W_0 - W)}{\rho_w(1+W_0)}$	Torrez Irigoyen and Giner (2011a)
Operating fluidisation velocity	$v_0 = 1.5(2.646(-\exp(-0.490W_m)) + 1.189))$	Torrez Irigoyen and Giner (2011b)
Sorption isotherm model (modified Halsey)	$W = 0.01\left[\frac{-\exp(A_{HM})}{\ln a_w}\right]^{1/R_{HM}}$ $A_{HM} = 1.595, R_{HM} = 1.117$	Torrez Irigoyen and Giner (2014)
Heat of desorption of water in the grain	$L_g = L_W + \frac{R_g T_k^2}{M_w}\left(\frac{\partial(\ln(a_w))}{\partial T_k}\right)_w$	Torrez Irigoyen et al. (2014)
Diffusion coefficient as function of grain temperature and moisture content	$D_{eff} = D_\infty \exp(-E_a/(R_g T_k))\left(1 - a\frac{\rho_0(W_0 - W)}{\rho_w(1+W_0)}\right)^{2/3}$ $E_a = 51.9$ kJ/mol, $D_\infty = 0.0237$ m^2/s	
Specific heat	*Moisture content below 0.7 kg water/kg dry matter* $C_p = 1638.08 + 3566.19W_m$ *For W_m above 0.7* $C_p = 837.4 + 4187W_m$	

$$[\rho_a v_0 S]\varDelta H_a + m_{SB}\frac{dH_s}{dt} = 0 \tag{3}$$

$$[\rho_a v_0 S]\left\lfloor C_{pda}(T_{a2} - T_{a1}) + L_{W0}(x_{a2} - x_{a1}) + C_{pwv}(T_{a2}x_{a2} - T_{a1}x_{a1})\right\rfloor + \ldots m_{SB}\left[(C_{ps} + C_{pw}W_m)\frac{dT_{sm}}{dt} - C_{pw}T_{sm}\left(-\frac{dW_m}{dt}\right)\right] = 0 \tag{4}$$

When solving the energy balance for each time, the specific heat was evaluated using the bed moisture content at that instant. Eq. (4) indicates that the energy transferred by forced convection from the air is utilized partly as latent heat of water evaporation and partly as sensible heat, which increases bed temperature.

Assari et al. (2013) suggest that mathematical modeling of fluidised beds requires two steps: the first one is composed by the description of the mathematical model, which has been done already, and the second, implies the description of all properties and parameters utilized for solving the model. They are shown in Table 1.

These relationships were developed in a previous research and are supported by a theoretical background with fitting parameters bearing physical meaning.

3. Numerical solution

3.1. Bed drying rate

The microscopic mass balance with variable diffusivity and shrinking particle volume was solved for a prescribed boundary condition ($W = W_e$) (Torrez Irigoyen and Giner, 2014). Here, a time-varying equilibrium moisture content was calculated, a consequence of the variation of outlet air conditions.

3.2. Heat transfer rate in the bed

Assuming that a perfect mixing of the grains takes place in the fluidised bed and that the air leaves the bed in thermal equilibrium with the solids, $T_{a2} = T_{sm}$ so the following expression can be deduced from Eq. (4)

$$\frac{dT_{sm}}{dt} = \frac{-[\rho_a v_0 S]\left\lfloor C_{pas}(T_{sm} - T_a) + L_{W0}(x_{a2} - x_{a1}) + C_{pv}(T_{sm}x_{a2} - T_a x_{a1})\right\rfloor}{m_{SB}\ (C_{ps} + C_{pw}W_m)} + \frac{C_{pw}T_{sm}}{(C_{ps} + C_{pw}W_m)}\left(-\frac{dW_m}{dt}\right) \tag{5}$$

This is an ordinary differential equation (ODE) with variable coefficients relating the variation of the mean grain bed temperature with time. A similar equation was proposed by Robbins and Fryer (2003) who, by studying the fluidised bed roasting of barley, have analyzed the heat and mass transfer phenomena. The initial conditions for Eq. (5) were the following:

$$T_{sm} = T_0 \quad t = 0 \tag{6}$$

The coupled macroscopic energy balance was integrated by the Euler method because very short time steps were utilized, for which it was sufficiently accurate. The variation of outlet air humidity can be computed by solving Eq. (2)

$$x_{a2} = x_{a1} + \frac{\left(-\frac{dW_m}{dt}\right)m_{SB}}{\rho_a V_0 S} \tag{7}$$

The equations presented here (1–7) constitute the bed level model for drying–toasting of soybean in a fluidised bed. The main steps of the calculations flow are summarized below, which were implemented in MATLAB 7.0 (The MathWorks Inc., USA):

0. From the initial values of the soybean, W_0, T_0, R_0, and the air temperature T_{a1}, start calculations at $t = \triangle$t.
1. Obtain the positions of radial nodes within the grain.
2. Solve the microscopic mass balance.
3. Calculate the average grain moisture content and thus the bed drying rate (- dW_m/dt).
4. Solve the macroscopic mass balance of water in the bed to find x_{a2}.

5. Solve the macroscopic energy balance in the bed to find T_{sm}.
6. Update the soybeans radius using the average moisture content and the shrinkage relationship.
7. Update time, $t = t + \triangle t$
8. If the final time of 60 min is reached, then stop calculation, otherwise return to step 1.

3.3. Model validation

The prediction capability of the model developed here are evaluated by using the absolute average deviation (ADD), in order to compute prediction errors in the same units as the dependent variable:

$$AAD = \frac{1}{n}\sum_{i=1}^{n}\left|y_{\exp,i} - y_{\mathrm{pred},i}\right| \tag{8}$$

a form of percentage error was calculated dividing ADD by the time-averaged experimental value

$$\%\ Error = \frac{ADD}{average\ value} \tag{9}$$

4. Thermal efficiency

Giner and De Michelis (1988) found that the possibility of adopting fluidised bed dryers in food technology is strongly dependent on an efficient use of energy. The most representative definition of thermal efficiency for a drying process is perhaps the following

$$E_f = \frac{Latent\ heat\ required\ to\ evaporate\ grain\ moisture}{Heat\ supplied\ to\ the\ drying\ air} \tag{10}$$

This can be expressed in terms of the operation parameters as

$$E_f = \frac{\rho_{S0}(1-\varepsilon_0)Z_{\max}\left(W_0 - W_{mf}\right)L_g}{\rho_a v_m C_{pa}(T_{a1} - T_{aM})t_d} \tag{11}$$

where v_m is the average superficial air velocity during the process.

5. Material and methods

5.1. Materials

Soybeans variety Don Mario 5.5 i were provided by Don Mario Semillas (Don Mario Seeds Company), Chacabuco, Provincia de Buenos Aires, Argentina. Moisture content of raw soybean at reception was 0.113 (±*0.001*) kg water/kg dry matter.

5.2. Experimental procedure

5.2.1. Preliminary operations

Grains were cleaned carefully and then immersed in drinking water using a water to soybean mass ratio of 2:1, and allowed to soak for 24 h at 10 °C. To facilitate fluidisation of particles at the beginning of drying–toasting, the soaked soybeans were previously surface-dried at 50 °C for 10 min by utilizing an automatically controlled, mechanical convection oven (Torrez Irigoyen and Giner, 2014).

5.2.2. Drying–toasting in fluidised bed

The drying–toasting experiments were conducted in a purpose-built fluidised bed dryer with automatic control of inlet air temperature and air velocity (Torrez Irigoyen and Giner, 2011*a*). The drying–toasting process was carried out with air inlet temperatures between 100 and 160 °C, at variable air velocities ranging from 3.9 to 1.8 m/s which allows the bed to maintain a high degree of mixing and, therefore, uniform treatment of the bed while reducing energy expenditure (Torrez Irigoyen and Giner, 2011b). The fixed bed height of products was 0.10 m in all experiments. The bed thermal history was recorded using a non-contact infrared thermometer Testo 830 T2 (Testo AG, Germany). Each point was an average of three readings, carried out every two minutes along the process.

5.2.3. Determination of moisture content

Moisture content was measured in triplicate 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 (air velocity, 0.25 m/s) Sanjor Model SL30SDB, Argentina was utilized. For weighing the samples, an Ohaus analytical balance was utilized with an accuracy of 0.0001 g. All samples were extracted from the bed at several times, from 0 to 60 min. Moisture content results were expressed in kg water/kg dry matter, units that are often referred to as “decimal dry basis” or “dec., d.b”.

5.2.4. Statistical analysis

Triplicate experiments were carried out for each fluidisation condition, measuring moisture content and temperature as a function of time. The different conditions were compared by the Tukey's test (Montgomery, 1991), at a confidence level of 95%.

6. Results and discussion

6.1. Validation of model

The Tukey's test revealed non-significant differences (at a confidence level of 95%) between the experimental moisture content and temperatures in all cases. The accuracy of modeling was determined by comparing model-predicted values with the experimental data. The Fig. 1, shows the experimental bed moisture content as a function of time, for all drying–toasting treatments.

Moisture content is observed to decrease faster at first, then more slowly until reaching almost an equilibrium value. Thomas and Varma (1990) who studied the fluidised bed drying of granular foods in a temperature range close to boiling point of water have observed a similar behavior.

Fig. 2 shows the variation of the average bed temperature with drying–toasting time. The grain temperature increased approaching near equilibrium with the drying air temperature after some 30 min in coincidence with Robbins and Fryer (2003), who studied the spouted-bed roasting of barley at high temperatures.

As can be seen in Table 2 the comparison was found to be quite

Table 2
Validation of the fluidised bed drying–toasting model. Comparison between model-predicted values and experimental data.

	Drying–toasting temperature, °C			
	100	120	140	160
Prediction capability				
ADD				
W	0.023	0.043	0.022	0.035
T	3.4	3.6	2.5	4.8
%Error				
W	4.3	11.2	6	10.5
T	3.6	3.2	1.9	3.2

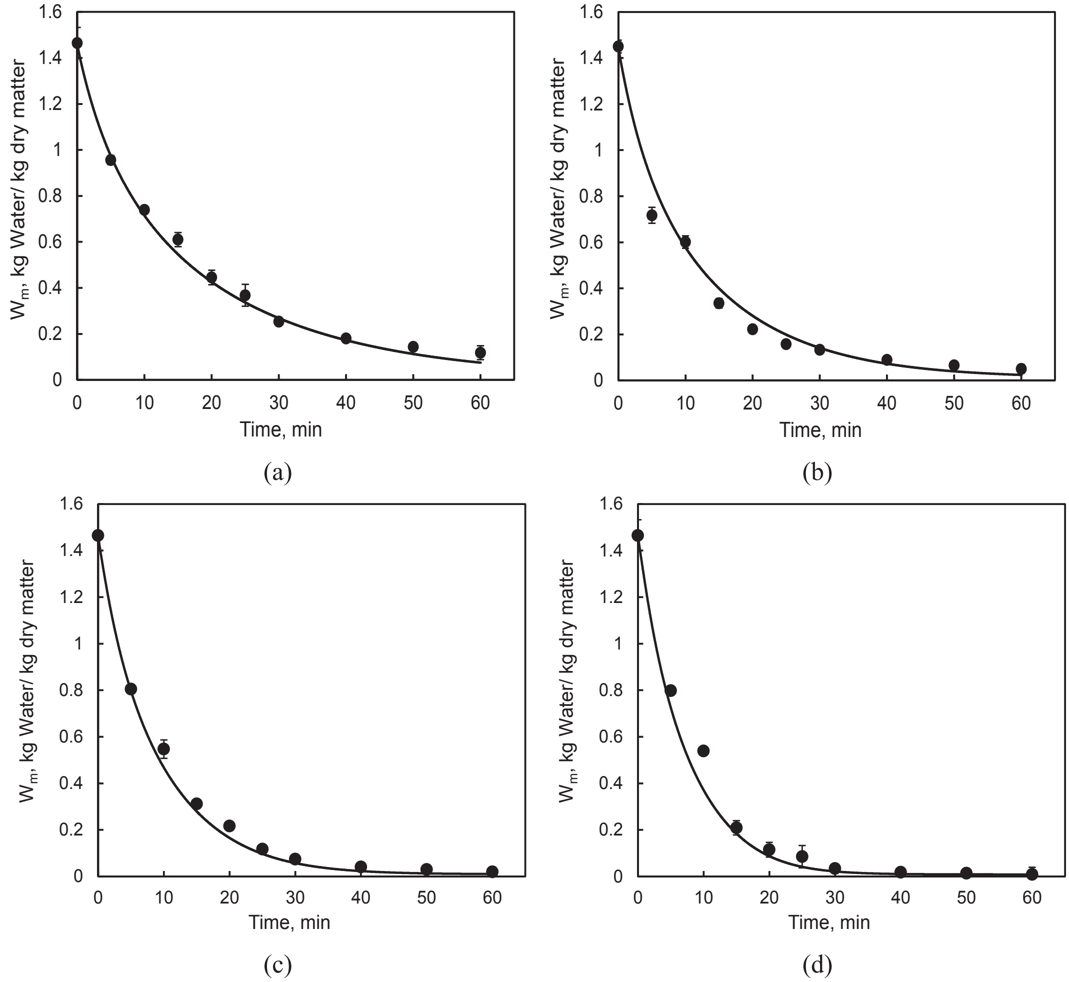


Fig. 1. Validation of the drying–toasting model in fluidised bed for presoaked soybean. Model-predicted moisture contents (solid line) and experimental data (symbols) are plotted for various inlet air temperatures: (a) 100 °C, (b) 120 °C, (c) 140 °C and (d) 160 °C.

satisfactory considering that the range of variation of both bed moisture content and temperature were large in each experiment.

6.2. *Evolution of the absolute humidity at the bed outlet*

The outlet humidity is difficult to measure because of instrument limitations at the high outlet air temperatures. Therefore, they were calculated as a function of time by solving Eq. (7) and plotted in Fig. 3.

The outlet air humidity changed considerably during drying toasting due to the presence of a bed 0.1 m deep. In the first minutes, a small increase in bed drying rate is predicted as a consequence of bed heating, leading to a maximum in the outlet air absolute humidity. Then, as bed drying rate decreases, so does the outlet air absolute humidity until reaching an asymptote defined by the inlet air humidity. As can be observed in Fig. 3, the curves at 100–120 °C have a lower initial increase in absolute humidity and a higher final value compared with those from the hotter curves at 140–160 °C. Although these changes are to be expected few studies have analyzed the variation air conditions in a fluidized bed of foods. For instance Markowski et al. (2010) studied the drying of barley in an spouted-bed but at lower temperatures and narrower moisture content range.

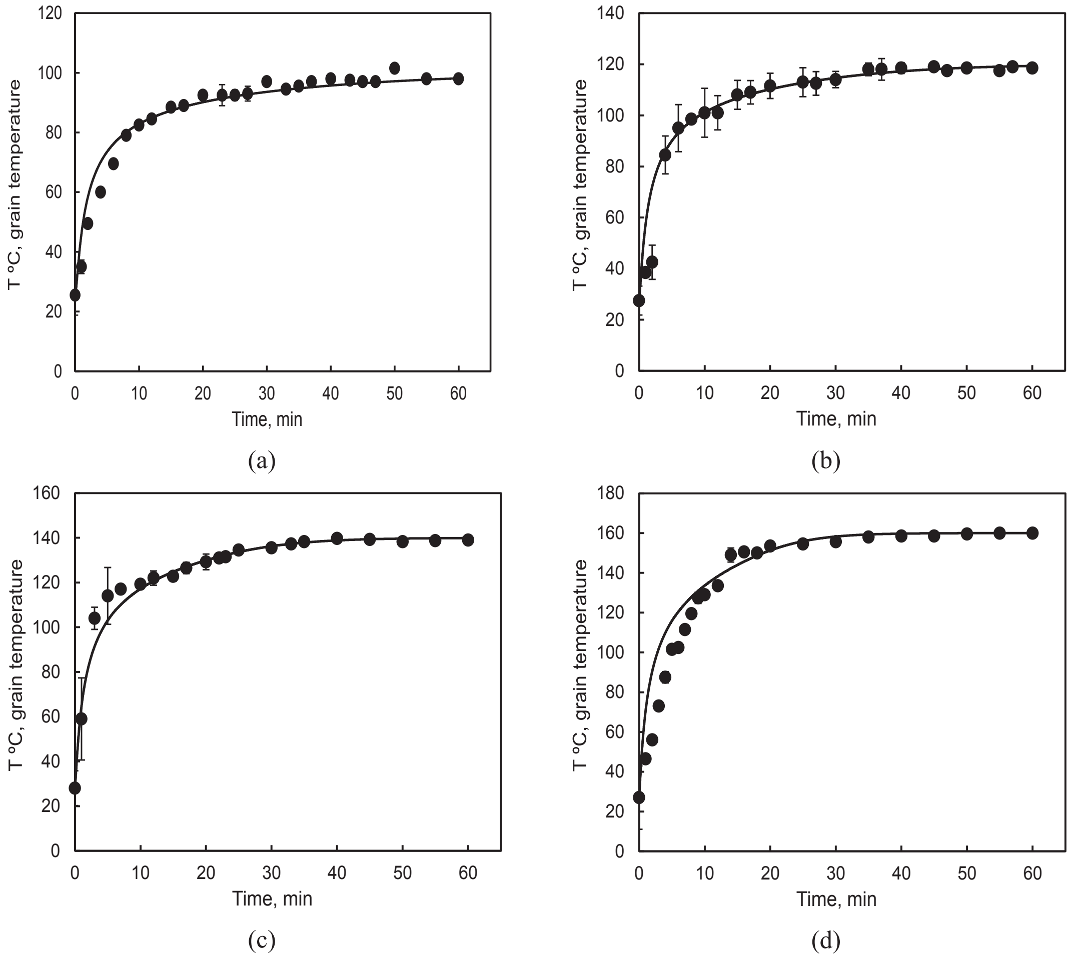
The Fig. 4 shows the variation of air relative humidity in a semilog-form with time at the dryer outlet. Here the maximum is not observed, so this variable diminishes almost from the beginning of the process, towards the air inlet value.

This behavior of the drying–toasting process is the result of the air passing through an initially wet bed of grains. As the product experiences loss of moisture, the drying rate decreases and the air was carrying less and less water out of the system per unit time, tending towards the inlet air conditions at the end of the process. Therefore, the outlet air was becoming drier and hotter with the progress of drying–toasting, and these conditions may favor energy recovery by recirculating a fraction of this air.

6.3. *Simulation of drying–toasting at different bed heights*

The model developed was utilized for simulating the drying–toasting curves and grain bed temperature for an inlet air of 140 °C at different bed heights between 0.1 and 0.3 m, in order to corroborate the consistency of predictions. This inlet air temperature was selected upon previous results (Torrez Irigoyen and Giner, 2011b). Bed moisture content and temperature were plotted as a function of time in Fig. 5.

As expected, by increasing the bed height, bed drying and heating rates are lowered and all curves tend to the same asymptotes, thus demonstrating model robustness. This enable us to further develop and explore the use of the model in that range of bed heights in order to evaluate thermal efficiency.



(a) (b)

(c) (d)

Fig. 2. Validation of the drying–toasting model in fluidised bed for presoaked soybean. Experimental (symbols) and model-predicted grain temperatures (solid lines) as a function of drying–toasting time of presoaked soybean, for inlet air temperatures of: (a) 100 °C, (b) 120 °C, (c) 140 °C and (d) 160 °C.

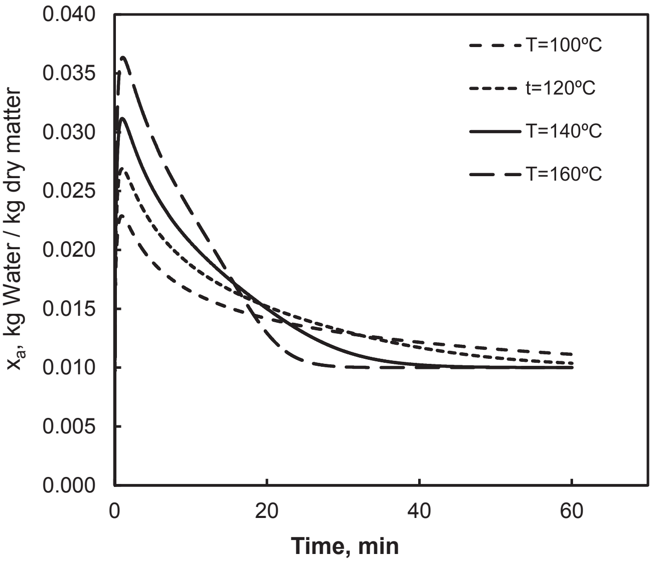


Fig. 3. Model-calculated outlet air absolute humidity as a function of time for the fluidised bed drying-toasting of soybean at all treatments.

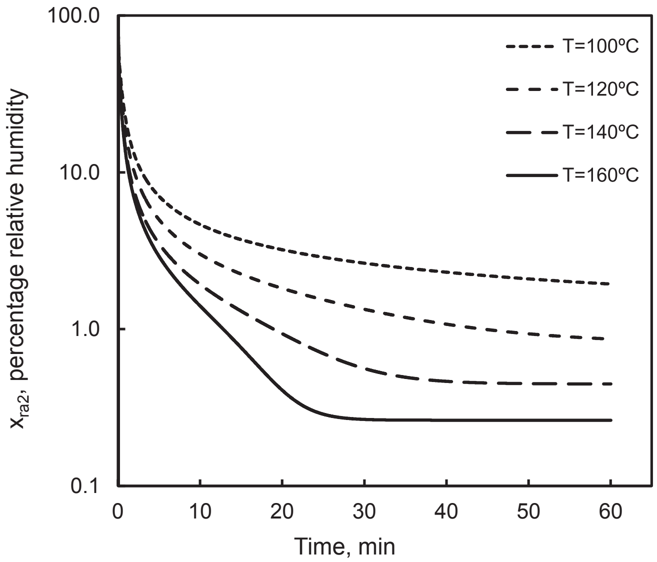
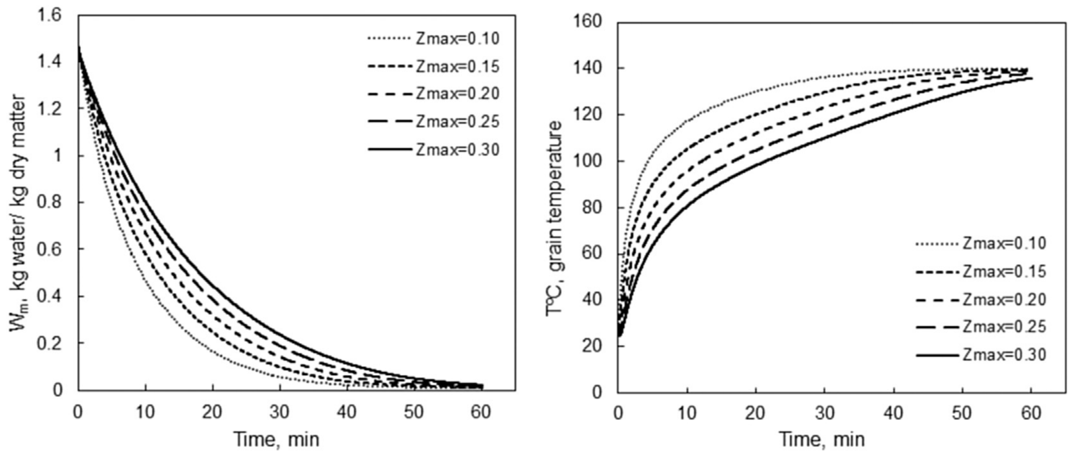


Fig. 4. Calculated values of outlet air relative humidity plotted in semi-log form as a function of time for the fluidised bed drying–toasting of soybean at all treatments.



(a) (b)

Fig. 5. Simulated moisture content (*a*) and grain temperature (*b*) curves as a function of time, for an inlet air temperature of 140 °C and bed heights from 0.1 to 0.3 m.

Table 3
Thermal efficiency of the fluidized bed dryer toaster at different bed heights without air recirculation. Inlet air temperature = 140 °C; inlet air absolute humidity = 0.01 kg vapor/kg dry air.

Z_{max} m	W_{mf} kg water/kg dry matter	T_{mf} °C	E_f %
0.10	0.009	140.0	9.1
0.15	0.010	140.0	13.1
0.20	0.010	139.8	16.9
0.25	0.012	139.1	20.5
0.30	0.016	136.8	23.9

6.4. *Evaluation of the thermal efficiency*

6.4.1. *Simulating the effect of different bed heights with no air recirculation*

By using the validated mathematical model, the thermal efficiency of the fluidised bed dryer was evaluated at different bed heights by using Eq. (11). For this purpose an inlet air temperature of 140 °C was considered with an inlet absolute humidity value of 0.01 kg water vapor/kg dry air, while several bed heights between 0.1 and 0.3 m were simulated for 60 min processes. Table 3 shows the final bed moisture content and temperature predicted with the drying model, as well as the calculated thermal efficiency.

An increase in the bed height from 0.1 to 0.3 m leads to a rise in thermal efficiency from 9.1 to 23.9% while the increase in the final bed moisture content was very small. While the simulation indicates that higher bed depths increases the efficiency, their values are still low and higher bed depths are normally not used in food fluidisation. Therefore, a system with air recirculation has to be examined.

6.4.2. *Simulating different bed heights with air recirculation*

In order to explore the potential of recirculated air it is convenient to conceptually transform the batch operation tested into an equivalent steady-state continuous system. To this end, a fraction of the outlet air will be discarded (purged) to recirculate the rest. In order to satisfy the mass balance of dry air, a dry mass of ambient air per unit time equal to that purged is incorporated. As seen on Fig. 4, very low outlet relative humidities are predicted for most of the process, so, 90% of the outlet drying air was considered for recirculation (in a 60 min process this implies to purge the outlet air from the first six minutes and recirculate that from the remaining 54 min). This approach is in agreement with Wiriyaumpaiwong (2002) who, by studying the drying of soybeans in a spouted bed has recommended a recirculation range to be between 80 and 90% of the outlet airflow. The concept proposed in this work is shown in Fig. 6.

The recirculated stream is mixed with ambient air ($T_{amb} = 20$ °C and $x_{amb} = 0.01$ kg water/kg dry air) to create a current that is heated to the inlet air temperature (T_{a1}) of 140 °C. The air temperature entering the heater (T_{aM}) is now above than the ambient value as a result of recirculation (Fig. 6). Then, the increase towards the inlet air temperature T_{a1} would involve a lower energy input. Stable inlet conditions of ambient humidity for the equivalent steady-state process with air recirculation was reached after several iterations with mass and energy balances in the whole dryer. Stable conditions were assumed to be achieved when the absolute humidity of the mixed air in two successive iterations had a difference lower than 1×10^{-4} kg water vapor/kg dry air. Fig. 7 shows the thermal efficiencies of the process for different steady-state conditions compared with the process without air recirculation.

From the results shown in Fig. 7, by recirculating 90% of the exhaust air, thermal efficiency was observed to rise from 9.1 to 39.3% for a bed height of 0.1 m and from 23.8 to 62.7% 0.3 m. Therefore, air recirculation and higher bed heights increase thermal efficiency. However, the latter condition has to be weighted with caution, since thicker beds demand more ventilation power and higher initial investment, leading to more noisy operation. Some authors as Ozari and Demir (2015) who studied the effect of mass of bed in the energy efficiency during drying grains in spouted bed reported a similar increase in thermal efficiency for higher bed heights. Regarding the final bed moisture content, the results were plotted for conditions with and without air recirculation in Fig. 8.

The increase in bed height leads to higher final moisture contents of the bed. Torrez Irigoyen and Giner (2011a) have found by experiment that the final moisture content should not be higher than 0.02 kg water/kg dry matter to keep the crispy nature of the snack. Therefore, bed heights below 0.3 m would be recommended for this process.

The dependence of recirculated air temperature and absolute humidity was evaluated as a function of bed height. As shown in Table 4, an increase in bed height leads to a decrease in the recirculated air temperature and to an increase of the absolute humidity. This behavior is a consequence of the air traversing a higher depth of moist grain: more heat has to be transferred and more

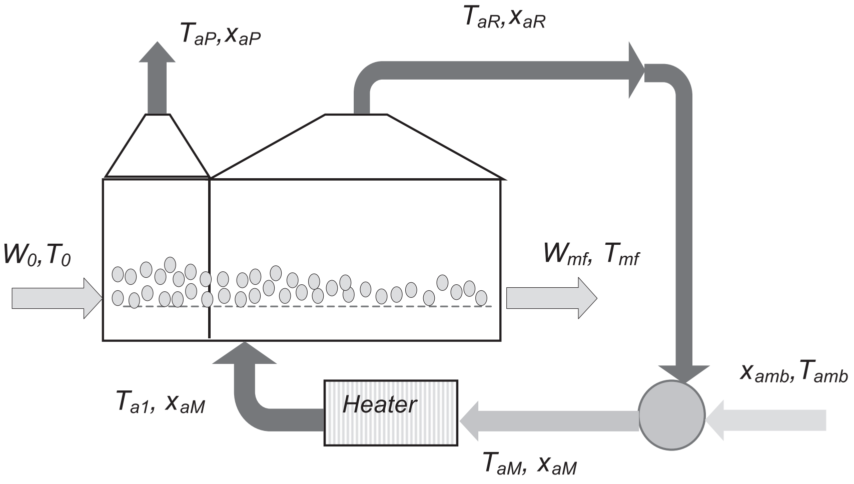


Fig. 6. A schematic drawing of drying–toasting fluidised bed system with air recirculation: values of humidity (x_a) and temperature (T_a) are identified by subscripts: *P* for purged, *R* for recirculated, *amb* for ambient and *M* for mixed.

water is received and carried away by the air. This fact also affects the conditions of the mixed air flow since the recirculated flow is colder and more humid.

In view of the data presented in Table 4 and considering Eq. (11), it would be possible to conceive that thermal efficiency can be improved at constant Z_{max} for decreasing differences between T_{a1} and T_{aM}. Torrez Irigoyen and Giner (2011b) have found that the drying toasting process can be carried out at decreasing fluidisation velocity with time; this procedure is another factor that reduce the demand of fan power and thermal energy which, coupled with the possibility of air recirculation contributes greatly to reduce energy consumption.

7. Conclusions

A previously developed mathematical model of the drying–toasting of presoaked soybean which considers local mass transport with shrinkage and variable diffusion coefficient at grain level was combined with macroscopic mass and energy balances in the drying air to develop a model at bed level and simulation program for fluidised beds.

Values of bed moisture content and temperature thus predicted were validated with the corresponding experimental data measured in a wide range of grain moisture contents and

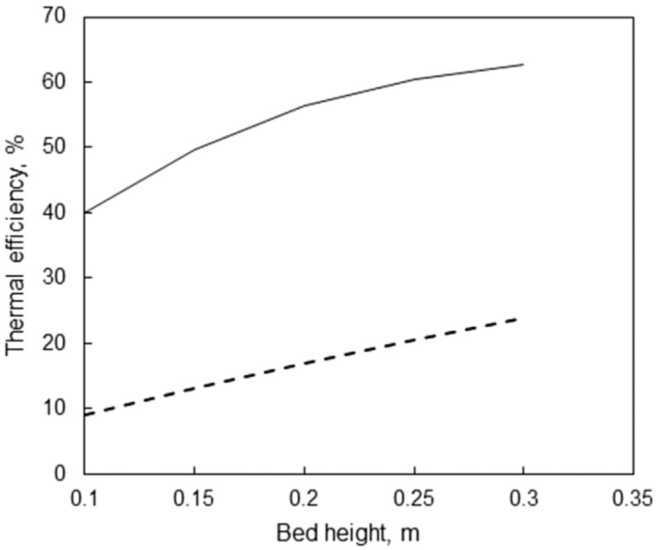


Fig. 7. Thermal efficiency values obtained from the simulation of an equivalent steady-state process with air recirculation as a function of the bed heights (solid line), compared with the process without recirculation at the same inlet air temperature (dashed line).

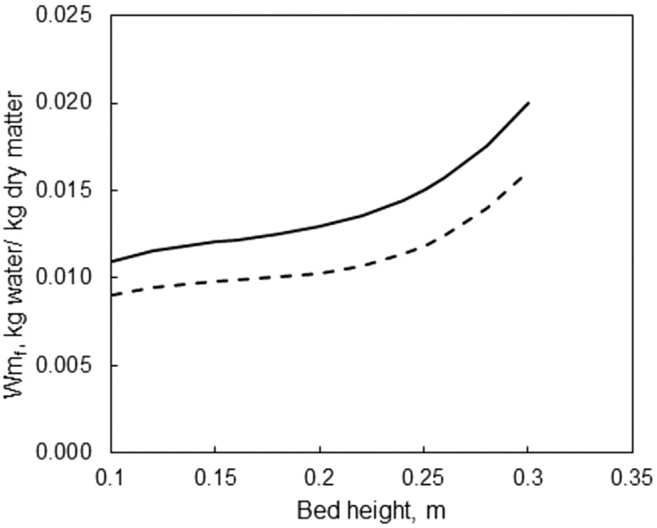


Fig. 8. Variation of final bed moisture content as a function of bed height for the equivalent steady-state process with recirculation (solid line) and the process without energy recovery (dashed line).

Table 4
Effect of bed height on absolute humidity (x_{aR}) and temperature (T_{aR}) of recirculated air, as well as on the absolute humidity (x_{aM}) and temperature (T_{aM}) of mixed air flow.

Z_{max} m	x_{aR} kg water/kg dry air	T_{aR} °C	x_{aM} kg water vapor/kg dry air	T_{aM} °C
0.10	0.024	132.9	0.021	109.4
0.15	0.035	127.7	0.030	105.8
0.20	0.047	122.2	0.040	102.0
0.25	0.061	116.5	0.051	98.1
0.30	0.075	110.8	0.063	94.1

temperatures (1.5–0.02 kg water/kg dry matter, and 20 °C–160 °C, respectively).

The outlet air relative humidity was then considerably low during the process, in the absence of recirculation so the need of using high airflows for supporting the bed during fluidization implied an underutilization of air as drying agent.

By simulating a system with recirculation of the outlet air corresponding to the last 90% of the process duration, the efficiency increased from 9 to 39% at 0.1 m and from 24 to 63% at 0.3 m, so the specific energy consumption during drying toasting can be substantially reduced.

This fluidised bed model is considered useful for product development as well as for equipment design, since drying–toasting times and energy consumptions were predicted for a wide range of operating conditions.

References

Akpinar, E.K., 2006. Determination of suitable thin layer drying curve model for some vegetables and fruits. J. Food Eng. 73, 75–84.

Alaathar, I., Hartge, E., Heinrich, S., Werther, J., 2013. Modeling and flowsheet simulation of continuous fluidized bed dryers. Powder Technol. 238, 132–141.

Assari, M.R., Tabrizi, H.B., Najafpour, E., 2013. Energy and exergy analysis of fluidized bed dryer based on two-fluid modeling. Int. J. Therm. Sci. 64, 213–219.

Bialobrzewski, I., Zielinska, M., Mujumdar, A.S., Markowski, M., 2008. Heat and mass transfer during drying of a bed of shrinking particles-simulation for carrot cubes dried in a spout-fluidized-bed drier. Int. J. Heat Mass Transf. 51, 4704–4716.

Di Scala, K., Crapiste, G., 2008. Drying kinetics and quality changes during drying of red pepper. Lebensm. Wiss. Technol. 41, 789–795.

Donsí, G., Ferrari, G., 1995. Heat transfer coefficients between gas fluidized beds and immersed spheres: dependence on the sphere size. Powder Technol. 82, 293–299.

Giner, S.A., Calvelo, A., 1987. Modelling of wheat drying in fluidized beds. J. Food Sci 52 (5), 1358–1363.

Giner, S.A., De Michelis, A., 1988. Evaluation of the thermal efficiency of wheat drying in fluidized beds: influence of air temperature and heat recovery. J. Agric. Eng. Res. 41, 11–23.

Jha, S.N., 2005. Mathematical simulation of roasting of grain. J. Food Eng. 71, 304–310.

Khalloufi, S., Almeida-Rivera, C., Bongers, P., 2010. A fundamental approach and its experimental validation to simulate density as a function of moisture content during drying processes. J. Food Eng. 97, 177–187.

Madhiyanon, T., Techaprasan, A., Soponronnarit, S., 2006. Mathematical models based on heat transfer and coupled heat and mass transfers for rapid high temperature treatment in fluidized bed: application for grain heat disinfestation. Int. J. Heat Mass Transf. 49, 2277–2290.

Markowski, M., Bialabrzewski, I., Modrzewska, A., 2010. Kinetics of spouted-bed drying of barley diffusivities for sphere and ellipsoid. J. Food Eng. 96, 380–387.

Martinez, M.L., Marín, M.A., Ribotta, P.D., 2013. Optimization of soybean heat-treating using a fluidized bed dryer. J. Food Sci. Technol 50 (6), 1114–1150.

Montgomery, D.C., 1991. Design and Analysis of Experiments, third ed. John Wiley and Sons Inc., New York, USA.

Ozahi, E., Demir, H., 2015. Drying performance analysis of a batch type fluidized bed drying process for corn and unshelled pistachio nut regarding to energetic and exergetic efficiencies. Measurement 60, 85–96.

Parmar, M.S., Hayrust, A.N., 2002. The heat transfer coefficient for a freely moving sphere in a bubbling fluidised bed. Chem. Eng. Sci. 57, 3485–3494.

Prachayawarakorn, S., Prachayawasin, P., Soponronnarit, S., 2006. Heating process of soybean using hot-air and superheated-steam fluidized-bed dryers. Lebensm. Wiss. Technol. 39, 770–778.

Robbins, P.T., Fryer, P.J., 2003. The spouted-bed roasting of barley: development of a predictive model for moisture and temperature. J. Food Eng. 59, 199–208.

Sander, A., 2006. Thin-layer drying of porous materials: selection of the appropriate mathematical model and relationships between thin-layer models parameters. Chem. Eng. Process. 46, 1324–1331.

Sun-Waterhouse, D., Teoh, A., Massarotto, C., Wibisono, R., Wadhwa, S., 2010. Comparative analysis of fruit-based functional snack bars. Food Chem. 119, 1369–1379.

Thomas, P.P., Varma, Y.B.G., 1990. Fluidised bed drying of granular food materials. Powder Technol. 69, 213–222.

Torrez Irigoyen, R.M., Giner, S.A., 2011a. Volume and density of whole soybean products during hot-air thermal treatment in fluidised bed. J. Food Eng. 102, 224–232.

Torrez Irigoyen, R.M., Giner, S.A., 2011b. Fluidisation velocities during processing of whole soybean snack. J. Food Eng. 107, 90–98.

Torrez Irigoyen, R.M., Giner, S.A., 2014. Drying-toasting kinetics of presoaked soybean in fluidised bed. Experimental study and mathematical modelling with analytical solutions. J. Food Eng. 128, 31–39.

Torrez Irigoyen, R.M., Goñi, S.M., Giner, S.A., 2014. Drying–toasting kinetics of presoaked soybean. A mathematical model considering variable diffusivity, shrinkage and coupled heat transfer. J. Food Eng. 142, 70–79.

Wiriyaumpaiwong, S., 2002. Comparative Study of Drying and Heating of Soybean. A dissertation submitted in partial fulfilment of requirement for the degree of doctor of philosophy (thermal technology). School of Energy and Materials King Mongkut's University of Technology Thonburi.

Yang, W.C., 2003. Handbook of Fluidization and Fluid-particle Systems (Chemical Industries), second ed. CRS Press, ISBN 0824748360.