Fluidised bed drying of soybeans

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Accepted 17 January 2000

Abstract

The fluidised bed drying characteristics of soybeans at high temperatures (110–140°C) and moisture contents, 31–49% dry basis, were modelled using drying equations from the literature. Air speeds of 2.4–4.1 m/s and bed depths from 10 to 15 cm were used. The minimum fluidised bed velocity was 1.9 m/s. From a quality point of view, fluidised bed drying was found to reduce the level of urease activity which is an indirect measure of trypsin inhibitor, with 120°C being the minimum required to reduce the urease activity to an acceptable level. Increased air temperatures caused increased cracking and breakage, with temperatures below 140°C giving an acceptable level for the animal feed industry in Thailand. The protein level was not significantly reduced in this temperature range. The drying rate equations and quality models were then combined to develop optimum strategies for fluidised bed drying, based on quality criteria, drying capacity, energy consumption and drying cost. The results showed that from 33.3% dry basis, soybean should not be dried below 23.5% dry basis in the fluidised bed dryer, to avoid excessive grain cracking. The optimum conditions for minimum cost, minimum energy and maximum capacity coincided at a drying temperature of 140°C, bed depth of 18 cm, air velocity of 2.9 m/s and fraction of air recirculated of 0.9. These conditions resulted in 27% cracking, 1.7% breakage and an energy consumption of 6.8 MJ/kg water evaporated. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Dehydration; Fluidised bed; Quality; Soybean
1. Introduction

Soybeans [Glycine max (L.) Merril] are harvested typically at moisture contents in the range 25–33% dry basis. Safe storage requires rapid decrease in moisture to preserve quality. Fluidised bed drying is recognised as a fast drying technology, due to the large air to product contact area achieved relative to a static bed caused by fluidisation of the product, and the high air speed and high temperatures used. Recently dryers have been commercialised in Thailand for paddy (80 units at 10 t/h capacity in private mills, Soponronnarit et al., 1998), with a few being used for maize and one unit being tested for soybean drying. The results of the soybean tests form the basis of this paper. Results showed that soybean could be dried at 110–140°C, with the degree of cracking increasing with temperature.

Soybean contains protein (17–19%) and fat (35–40%), providing a cheaper source of protein than meat. Raw soybean cannot be consumed as human food or animal feed because of the presence of antinutritional substances, some of which may harm the consumer. These antinutritional substances can be eliminated by heat treatment, provided the heat treatment is maintained at a level that does not significantly reduce the protein level of the legume. Fluidised bed drying is a high-temperature short-time treatment. Overhults et al. (1973) studied soybean (Culter type) drying from moisture contents of 25–30% dry basis to 11% dry basis, in a thin bed, at drying temperatures of 38–104°C. At high drying temperatures, the physical surfaces of the soybeans were damaged, with cracks in the form of V-shaped fissures. Hirunlabh et al. (1992) studied the strategies for the batch drying of soybeans at temperatures of 44–75°C, from moisture contents of 25-11% dry basis, finding that breakage and cracking increased with both drying time and temperature. Zeng et al. (1996) studied soybean breakage using air temperatures of 37.5, 48.9 and 60°C, from 19, 25 and 32% dry basis to a final moisture content of 12% dry basis, finding that breakage increased with both temperature and initial moisture content. A surprising result was that initial moisture content had no effect at 60°C. Kwok et al. (1993) studied the effect of heat treatment of soymilk on trypsin inhibitor activity (TIA). The pH was found to have a small effect, with greater variation in TIA at high pH. At a pH of 6.5, TIA was decreased by 90% in 60 min at 93°C, 56 s at 143°C and 23 s at 154°C.

Soponronnarit and Prachayawarakorn (1994) studied fluidised bed drying of paddy with temperatures of 100–150°C, initial moisture contents ranging from 28.5 to 45% dry basis, and specific airflow rates of 0.13–0.33 kg air/s.kg dry product. They found that increasing temperature or specific airflow rate improved the drying rate, and energy consumption decreased with specific airflow rate and air recirculation fraction. This led to a recommendation that the air temperature should not be higher than 115°C and final product moisture not less than 24% dry basis. Soponronnarit et al. (1996a) developed this study further, showing that a bed depth of 10 cm, specific airflow rate of 0.043 kg/s.kg, using 80% air recirculation, gave optimum drying conditions. The energy consumption (verified in tests at commercial rice mills) showed that primary energy consumption varied from 2.5 to 4.0 MJ/kg water evaporated (Soponronnarit et al., 1996b).

This paper modelled the drying rate of soybean in a fluidised bed and the effect of fluidised bed drying on quality aspects of soybean. In order to develop recommendations for dryer operation and design for soybean, the drying rate model and quality model were combined
into a model of a complete drying system, and this was used to determine suitable operating conditions for the dryer.

2. Materials and methods

2.1. Thin layer drying rate

Three thin layer models of the drying rate of soybeans were fitted to the data, namely Newton’s Law of Cooling, and the models of Page (1949) and Sharaf-Eldeen et al. (1980). The models were compared to determine the best model for predicting drying rate. The three models were:

Newton’s Law of Cooling:

\[ MR = \exp(-k_1t) \]  

where \( MR \) is the moisture ratio defined as:

\[ MR = \frac{M - M_{eq}}{(M_0 - M_{eq})} \]  

where \( k_1 \) = drying constant (min\(^{-1}\)), \( t \) = time (min), \( M \) = moisture at time \( t \) (decimal dry basis), \( M_0 \) = initial moisture content (decimal dry basis) and \( M_{eq} \) = equilibrium moisture content (decimal dry basis). The equilibrium moisture content was calculated using the equation of Tia et al. (1990):

\[ RH = \exp\left[\left(\frac{-21065}{R \cdot T}\right) \cdot M_{eq}^{-1.25}\right] \]  

where \( RH \) is the air relative humidity (fraction), \( T \) is the air temperature (Kelvin) and \( R \) is the gas constant (8.314 J/mol.K).

Page’s (1949) equation:

\[ MR = \exp(-k_2t^n) \]  

where \( k_2 \) and \( n \) are constants.

Sharaf-Eldeen et al.’s (1980) equation (two-compartment model):

\[ MR = A \exp(-k_3t) + B \exp(-k_4t) \]  

where \( k_3, k_4, A \) and \( B \) are constants. This model was used by Tumambing and Driscoll (1991) for fluidised drying of paddy, where the constants \( A, B, k_3 \) and \( k_4 \) were found to depend on temperature and bed depth. Prachayawarakorn and Soponronnarit (1993) also used Eq. (5) in a model of the fluidised bed drying of paddy, finding that constants \( A, B, k_3 \) and \( k_4 \) were dependent on temperature and specific airflow rate (airflow rate per unit product mass). They also found that Page’s (1949) equations fitted the data as well as the two-compartment model. Satayaprasert and Vanishsriwatana (1992) used Newton’s Law of Cooling for fluidised drying of maize, showing that \( k_1 \) was a function of temperature and bed depth.
A batch fluidised bed dryer (Fig. 1) was used. This consisted of a cylindrical chamber with an inner diameter of 20 cm, a height of 140 cm, four 3 kW electric heaters, a temperature controller with on-off control and a backward-curved blade centrifugal fan (1.5 kW motor) with mechanical variable speed drive. Two cylindrical chambers were used, one of transparent acrylic used for minimum fluidised bed speed tests, and the other of stainless steel used for drying tests. A water manometer was used for pressure drop measurements. Temperatures were measured using Chromel-Alumel (Type K) thermocouples (not shielded against radiation) connected to a data logger with an accuracy of ±1°C. Air speed was measured at the locations where flow was well developed (in the straight duct as indicated in Fig. 1) by a hot-wire anemometer with an accuracy of ±5%. A pitot-static tube was not used due to the difficulty of reading the water level difference in a U-tube.

The soybean was rewetted from its delivery moisture and then equilibrated in a cool room at 8–10°C for 5–7 days to ensure uniform moisture content through the kernels. The experimental conditions used were initial moisture contents of 24.7–33.3% dry basis, bed depths of 10–15 cm, temperatures of 110–140°C and air speeds of 2.4–4.1 m/s. Samples were taken at 2, 5, 10, 15 and 20 min intervals, and then dried in an electric oven at 103°C for 72 h in order to measure final moisture content.

2.2. Quality

Measurements of quality were taken from drying runs at moisture contents of 32.1 and 33.3% dry basis and 100–140°C air temperature, and at 14.9% dry basis using air

![Fig. 1. Diagram of a batch fluidised bed dryer.](image-url)
temperatures of 140–160°C, to test whether drying was sufficient treatment or whether a high temperature treatment for the dried product could be used.

Urease activity was measured. It is an indirect test for level of trypsin inhibitor (Cheong, 1997). It measures the change in pH resulting from the action of urease converting urea to ammonia. The time required for complete digestion is 30 minutes. Soluble protein was measured by dispersion of soybean proteins in 0.2% KOH (Cheong, 1997). Cracking was assessed visually.

The measured values of urease activity were expressed as ΔpH.

2.3. System model

Soponronnarit et al. (1996a) developed a mathematical model of a continuous cross-flow fluidised bed paddy dryer. The authors assumed thermal equilibrium between the drying air and paddy within the drying chamber. This model was modified for soybean drying, and the quality model incorporated. Fig. 2 is a diagram of the dryer, showing five control volumes labelled CV1 to CV5. The dimensions of the first control volume (drying chamber) were 1.25 m height by 2.5 m length by 1.0 m width. Experimental results reported by Sripawatakul (1993) indicated that the flow regime of paddy was between near plug flow and high dispersion flow. Though dispersion was a known factor in the fluidised bed, the model assumed plug-flow in order to simplify calculation. The assumption of plug flow and thermal equilibrium between the product and the drying air was validated for both paddy and maize drying by Soponronnarit et al. (1996a) and Soponronnarit et al. (1997), respectively. Simulated and experimental results of average moisture content of paddy at the dryer exit were in agreement.

Fig. 2. Schematic diagram of a model continuous fluidised bed dryer.
3. Results and discussions

3.1. Thin layer drying rate

Fig. 3 shows that the minimum superficial air speed required for fluidisation was 1.9 m/s. This varied slightly and inversely with moisture content, since as moisture content increases, bulk density decreases but porosity increases, increasing the buoyancy forces. The minimum fluidisation air speed also increased with bed depth. Typical fluidisation behaviour was observed above the minimum fluidisation speed, with gas bubbles being formed above the distributor and moving to the bed surface.

The drying rate increased with air temperature, \( T \) (Fig. 4) and specific airflow rate, \( v_s \) (Fig. 5). All parameters in each of the models of Eqs. (1), (4) and (5) were therefore fitted to functions of \( T \) and \( v_s \). The following parameter models were tested:

1. The general first order polynomial model, including a cross-product term of the form \( v_sT \),
2. The general second order polynomial,
3. The Arrhenius temperature dependence model:
   \[
   \text{parameter} = cv_s^n \exp\left(\frac{-\Delta h}{RT}\right)
   \]  
   where \( \Delta h \) is an activation energy and \( c \) and \( n \) are constants,
4. The power model:
   \[
   \text{parameter} = kv_s^{n_1}T^{n_2}
   \]  
   where \( k \), \( n_1 \) and \( n_2 \) are constants.

![Fig. 3. Relationship between pressure drop and air velocity at different bed depths (moisture content of soybean = 12.5% dry basis).](image-url)
Fig. 4. Evolution of moisture content of soybean at different drying temperatures (specific air flow rate = 0.03 kg/s/kg dry soybean, bed depth = 15 cm).

Fig. 5. Evolution of moisture content of soybean at different specific airflow rates (drying air temperature = 120°C, air velocity = 2.5 m/s).
After fitting each model to each parameter, the most appropriate model was chosen using the standard error of prediction as the determinant.

\[
\text{ASPE} = \frac{\sum_{i=1}^{n} (\text{MR}_{\text{obs}} - \text{MR}_{\text{pre}})^2}{n}
\]

(8)

where ASPE is the average squared prediction error, MR_{obs} is the moisture ratio determined by experiment, MR_{pre} is the predicted moisture ratio as determined by the regression equation, and \( n \) is the number of data points. The results are given in Table 1, showing that Page’s (1949) model gave the lowest error in prediction. The two-compartment model also performed well, but used a greater number of parameters. Based on this result, the thin layer drying equation best suited to soybean was Page’s (1949) equation, with the following constants:

\[
k_2 = -0.529 + 4.42v_s + 0.00143T - 0.00704v_sT
\]

(9)

\[
n = 3.50 - 116v_s - 0.00600T + 0.290v_sT
\]

(10)

with correlation coefficients of 80% for \( k_2 \) and 84% for \( n \).

3.2. Effect on cracking and breakage

Soybean drying by fluidisation at high temperatures caused soybeans to crack and break in V-shaped fissures. Experimental results were consistent with those of Overhults et al. (1973) that cracking and breakage of soybean increased with drying temperature as heat and mass transfer rates increased. Since water movement is limited by water diffusion in the soybean kernel, the temperature of the soybean surface increases to more than the air wet bulb temperature as drying proceeds, so that the soybean becomes brittle at the surface and prone to cracking.

The average degree of soybean cracking in the animal feed industry was not available. However, the degree of breakage must be <3%. The results show that soybean drying can be operated with air temperatures up to 140°C.

Mathematical models were developed to predict the percentage of cracking and breakage of soybean as a function of the initial moisture content (\( M_0 \), dry basis), final moisture content

<table>
<thead>
<tr>
<th>Model</th>
<th>ASPE</th>
<th>Second order polynomial</th>
<th>First order polynomial</th>
<th>Arrhenius-type equation</th>
<th>Power Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Page</td>
<td>0.000922</td>
<td>0.000251</td>
<td>0.000462</td>
<td>0.000459</td>
<td></td>
</tr>
<tr>
<td>Two-compartment</td>
<td>0.000286</td>
<td>0.000504</td>
<td>0.000446</td>
<td>0.002222</td>
<td></td>
</tr>
<tr>
<td>Newton’s law of cooling</td>
<td>0.000455</td>
<td>0.000574</td>
<td>0.000684</td>
<td>0.001407</td>
<td></td>
</tr>
</tbody>
</table>
(\(M_f\), dry basis) and drying temperature (\(T\), Kelvin). The model used was the Logistic equation, as follows:

\[
Cr = \frac{a}{1 + \exp(b(M_f - c))}
\]

(11)

where \(Cr\) denotes percentage of cracking, \(a\), \(b\) and \(c\) are constants. After fitting the equation to the data by least squares regression,

\[
a = -19.2 - 392M_0 + 0.185T + 0.949M_0T
\]

(12)

\[
b = -369 + 1322M_0 + 1.137T - 3.71M_0T
\]

(13)

\[
c = 0.151 - 0.0741M_0 - 0.000261T + 0.00155M_0T
\]

(14)

where correlations of 96%, 92% and 93% were measured for Eqs. (12)–(14) respectively. The same equation was applied to breakage:

\[
Br = \frac{d}{1 + \exp(e(M_f - f))}
\]

(15)

\[
d = -8.84 - 11.8M_0 + 0.0251T - 0.0190M_0T
\]

(16)

\[
e = -493 + 1763M_0 + 1.255T - 4.21M_0T
\]

(17)

\[
f = -1.82 + 6.08M_0 - 0.00392T - 0.0114M_0T
\]

(18)

where correlations of 73%, 54% and 97% were measured for Eqs. (16)–(18), respectively.

The usefulness of these models was gauged by considering the values of the average square prediction error (ASPE) between experimental and calculated results. The ASPE for cracking

![Fig. 6. Comparison between predicted and observed values of percentage cracking of soybean.](image)
and breakage were 8.27 (typically about 14% error in a model prediction) and 0.012 (typically about 0.4% error) respectively, as illustrated in Figs. 6 and 7. The models and data are plotted for comparison in Figs. 8 and 9. Thus the breakage model is of high accuracy.

### 3.3. Effect on nutrition factors

Acceptable values of urease activity (ΔpH) should be lower than 0.3, as required by the animal feed industry in Thailand.

Fig. 10 shows the relationship between urease activity and final moisture content. It was found that ΔpH decreased when final moisture content decreased, or drying times were excessive. In decreasing the level of ΔpH by fluidised bed drying, the air temperature must be higher than 120°C. Soybean drying at high temperature did not result in the decrease of protein as shown in Table 2. If soybean was dried to a moisture content of 12.2%–14.4% dry
basis, ΔpH and protein solubility levels met the acceptable standard values, i.e. ΔpH of less than 0.3 and protein solubility in the range of 80–85%.

The fluidised bed dryer was also used to reduce urease activity in soybean at initial moisture content of 14.9% dry basis. The results are given in Table 3 and Fig. 11, showing that protein solubility and ΔpH were within the range of acceptable values, and indicating that it is feasible to use the fluidised bed dryer for soybean drying. However, at drying temperatures of higher than 150°C, it was found that soybean overheated, with the result that protein solubility was reduced to lower than 80–83%. This may be avoided by reducing the drying time, but currently limits the maximum drying temperature at low moistures to about 140°C.

Fig. 9. Effect of final moisture content of soybean on percentage of breakage at different drying air temperatures (initial moisture content = 24.7% dry basis).

Fig. 10. Effect of final moisture content of soybean on urease activity (initial moisture content = 32.1% and 33.3% dry basis).
3.4. System model

The mean residence time in minutes of the product in the dryer is:

\[ \tau = \frac{h_u}{F} = \frac{\rho_c V}{F} = \frac{A_b \rho_c H}{F} \]  \hspace{1cm} (19)

where \( h_u \) is the amount of soybean in the dryer at any one time (hold-up mass), \( \rho_c \) is the soybean bulk density (kg/m\(^3\)), \( V \) is the product non-fluidised hold-up volume (m\(^3\)), \( F \) is the feed rate (kg/min), \( A_b \) is the bed surface area and \( H \) is the bed depth of the non-fluidised product in the dryer (m). With the assumption of plug-flow as stated before, the bed length was divided into \( N \) vertical elements, so a particle would stay in each element for a time \( t = \tau/N \). Similarly, the mass flow per element and holdup mass per element were obtained.

### Table 2
Protein solubility in 0.2% KOH and urease activity of high initial moisture soybean after drying at different temperatures\(^a\)

<table>
<thead>
<tr>
<th>( T(\degree C) )</th>
<th>( M_0 ) (%d.b.)</th>
<th>( M_f ) (%d.b.)</th>
<th>Protein (%)</th>
<th>Urease activity (( \Delta \rho ))</th>
<th>Protein solubility (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>140</td>
<td>33.5</td>
<td>23.3</td>
<td>40.76</td>
<td>0.67</td>
<td>86.14</td>
</tr>
<tr>
<td>130</td>
<td>32.1</td>
<td>22.0</td>
<td>39.75</td>
<td>0.90</td>
<td>86.76</td>
</tr>
<tr>
<td>120</td>
<td>33.5</td>
<td>24.0</td>
<td>40.53</td>
<td>0.83</td>
<td>88.96</td>
</tr>
<tr>
<td>140</td>
<td>33.5</td>
<td>14.4</td>
<td>40.14</td>
<td>0.10</td>
<td>81.78</td>
</tr>
<tr>
<td>130</td>
<td>32.1</td>
<td>12.2</td>
<td>40.67</td>
<td>0.11</td>
<td>81.70</td>
</tr>
<tr>
<td>120</td>
<td>33.5</td>
<td>12.8</td>
<td>41.33</td>
<td>0.11</td>
<td>82.43</td>
</tr>
<tr>
<td>Initial values</td>
<td></td>
<td></td>
<td>41.45–41.67</td>
<td>1.89–2.04</td>
<td>89.94–90.07</td>
</tr>
</tbody>
</table>

\(^a\) \( M_0 \) = initial moisture content, \( M_f \) = final moisture content.

### Table 3
Protein solubility in 0.2% KOH and urease activity of low initial moisture soybean (initial moisture content = 14.9% dry basis) after drying at three temperatures for different periods

<table>
<thead>
<tr>
<th>( T(\degree C) )</th>
<th>SP(^a)</th>
<th>Drying time (min)</th>
<th>( M_f ) (%d.b.)</th>
<th>Protein (%)</th>
<th>Urease activity (( \Delta \rho ))</th>
<th>Protein solubility (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>160</td>
<td>0.072</td>
<td>3</td>
<td>10.8</td>
<td>38.98</td>
<td>0.18</td>
<td>84.26</td>
</tr>
<tr>
<td></td>
<td>0.052</td>
<td>3</td>
<td>11.6</td>
<td>40.23</td>
<td>0.2</td>
<td>83.09</td>
</tr>
<tr>
<td></td>
<td>0.037</td>
<td>3</td>
<td>12.5</td>
<td>39.97</td>
<td>0.3</td>
<td>82.90</td>
</tr>
<tr>
<td>150</td>
<td>0.073</td>
<td>5</td>
<td>8.8</td>
<td>40.35</td>
<td>0.07</td>
<td>77.68</td>
</tr>
<tr>
<td></td>
<td>0.051</td>
<td>5</td>
<td>10.0</td>
<td>39.47</td>
<td>0.1</td>
<td>79.08</td>
</tr>
<tr>
<td></td>
<td>0.037</td>
<td>5</td>
<td>10.7</td>
<td>40.33</td>
<td>0.11</td>
<td>80.91</td>
</tr>
<tr>
<td>140</td>
<td>0.072</td>
<td>5</td>
<td>9.2</td>
<td>39.91</td>
<td>0.24</td>
<td>84.97</td>
</tr>
<tr>
<td></td>
<td>0.054</td>
<td>5</td>
<td>10.4</td>
<td>40.68</td>
<td>0.28</td>
<td>83.26</td>
</tr>
<tr>
<td></td>
<td>0.042</td>
<td>10</td>
<td>8.3</td>
<td>40.83</td>
<td>0.14</td>
<td>82.04</td>
</tr>
<tr>
<td>Initial values</td>
<td></td>
<td></td>
<td></td>
<td>40.97</td>
<td>2.08</td>
<td>88.45</td>
</tr>
</tbody>
</table>

\(^a\) SP = specific airflow rate (kg/s-kg solid).
The average moisture content of the soybeans at the outlet of the \(i\)th layer was obtained by differentiating Eq. (4) [using the constants given by Eqs. (9) and (10)] with respect to time, and substituting the mean residence time from Eq. (19). This moisture then became the inlet moisture content for the next layer. Energy and mass balances were used to calculate the air states for each element of the dryer:

\[
H_{fi} = H_a + h_u \frac{M_i - M_{i+1}}{m_a t_i}
\]  

\[
T_{fi} = (Q_1 + c_a T_a + H_a h_{fg} + c_v T_a) - H_{fi} h_{fg} + c_{pw} T_a h_u / m_a t_i - \Delta U / (c_a + H_{fi} c_v)
\]

where \(H_{fi}\) = absolute humidity of drying air leaving the \(i\)th element, \(H_a\) = absolute humidity of heated inlet air, \(T_{fi}\) = temperature of drying air leaving the \(i\)th element (°C), \(T_a\) = temperature of drying air entering the \(i\)th element (°C), \(m_a\) = mass flow rate of drying air (kg/s), \(t_i\) = small interval of drying time (s), \(Q_1\) = heat losses to surroundings (kW/kg dry air), \(c_a\) = specific heat of dry air (kJ/kg °C), \(c_v\) = specific heat of water vapor (kJ/kg °C), \(c_{pw}\) = specific heat of moist soybean (kJ/kg °C), \(h_{fg}\) = latent heat of vaporisation of moisture (kJ/kg) and \(\Delta U\) = change in internal energy of the soybean (kJ/kg dry air). The average temperature and absolute humidity of drying air leaving the drying chamber were determined by taking the arithmetic means of \(T_{fi}\) and \(H_{fi}\) over time.

Considering control volume, CV2, the temperature of the recirculation air before mixing with fresh ambient air, was determined from the following equation:

\[
T_{f2} = \frac{(Q_2 / m_a R_e) + c_a T_{f1} + H_{f1} c_v T_{f1}}{c_a + H_{f1} c_v}
\]

Fig. 11. Effect of final moisture content of soybean on urease activity (initial moisture content = 14.9% dry basis).
where $T_f=\text{temperature of recirculation air (°C)}$, $R_c=\text{fraction of air recirculation (} m_{Rc}/m_a \text{)}$ and $Q_2=\text{heat losses to surroundings (kW)}$.

For control volume CV3, the equations of mass and energy balance can be written as follows:

$$H_a = (1 - R_c)H_i + H_fR_c \tag{23}$$

$$m_a c_a T_x + m_a H_a (h_{fg} + c_v T_x) - m_i c_a T_i - m_i H_i (h_{fg} + c_v T_i) - R_c m_a c_a T_{f2} - R_c m_a H_{f1} (h_{fg} + c_v T_{f2}) = 0 \tag{24}$$

where $T_x=\text{temperature of drying air leaving control volume CV3 (°C)}$ and $T_i=\text{ambient air temperature (°C)}$.

For control volume CV4, the equation of energy balance can be written as follows:

$$Q_5 + Q_h = m_a (c_a + c_v H_a)(T_b - T_x) \tag{25}$$

where $Q_5=\text{convective and radiative heat losses to surroundings (kW)}$, $Q_h=\text{thermal energy consumption (kW)}$ and $T_b=\text{drying air temperature leaving the heater (°C)}$.

For control volume CV5, the conservation of energy law was applied to determine the temperature rise across the fan ($\Delta T_{fan}$):

$$\Delta T_{fan} = \frac{P_t}{1000 (\rho_a \eta_f)(c_a + c_v H_a)} \tag{26}$$

where $P_t=\text{pressure loss (Pa)}$, $\eta_f=\text{fan efficiency (fraction)}$ and $\rho_a=\text{density of drying air (kg/m}^3\text{)}$.

Pressure would change if either airflow rate, air recirculation ratio or soybean bed depth was changed. The electrical energy consumption of the fan motor, $W_M$ in kW, was determined from the equation below:

![Fig. 12. Relationship between cracking and breakage and drying air temperature at different final moisture contents (initial moisture content = 33.3% dry basis).](image)
\[ W_M = \frac{P(m_a/p_a)}{\eta_f \eta_m} \]  

(27)

where \( \eta_m \) is motor efficiency.

The above equations were solved under the following conditions: initial and final moisture contents of 32.3% and 23.5% dry basis, respectively, drying air temperatures of 110–140°C, ambient air 30°C, ambient relative humidity 70%, drying air velocity of 2.9 m/s and a fan motor of 37 kW.

Fig. 12 shows the effect of the drying air temperature on the percentage of cracking and breakage of soybean. It was found that if the moisture content of the soybean reduced to 20.5% dry basis, the percentage of cracking would be 10% higher than if the moisture only reduced to 23.5% dry basis. Minimum final moisture content of 23.5% dry basis was therefore adopted as a requirement for further work on investigating appropriate strategies for soybean drying.

Figs. 13–16 show the effect of fraction of recirculation air on drying capacity and energy consumption at different bed depths and drying air temperatures. Drying capacity increased with bed depth and air temperature, whilst energy consumption decreased. It was found that as air recirculation increased, energy consumption decreased rapidly and drying capacity decreased gradually, up to 0.9. Above this recirculation rate, energy consumption rapidly increased and drying capacity rapidly decreased.

Cost studies were conducted using the following data (US$ 1 = 40 Baht):

1. Cost of dryer : 850,000–911,130 Baht (depending on size of fan motor)
2. Life time of dryer : 10 years
3. Operating time : 12 h per day and 90 days per year
4. Maintenance cost per year : 5% of dryer cost
5. Salvage value : 10% of dryer cost
6. Interest rate : 18%/year
7. Diesel fuel price : 10 Baht/l
8. Electricity price : 1.55 Baht/kW.h

Fig. 13. Effect of air recirculation on drying capacity at different bed depths (initial moisture content = 33.3% dry basis, final moisture content = 23.5% dry basis, drying air temperature = 140°C, air velocity = 2.9 m/s).
Figs. 17–18 show the effect of air recirculation on drying costs at different bed depths and drying air temperatures. It was found that the optimum conditions for soybean drying by fluidised bed drying in terms of minimum drying cost were as follows: drying air temperature of 140°C, bed depth 18 cm and fraction of air recirculation 0.9. At these conditions, percentage of cracking was 27%, percentage of breakage was 1.74%, drying capacity was 4.65 tph, total primary energy consumption was 6.8 kW/MJ water evaporated [15% electric power (fan) and 85% burner] and total drying cost was 2.38 Baht/kg water evaporated.

Fig. 14. Effect of air recirculation on drying capacity at different drying air temperatures (initial moisture content = 33.3% dry basis, final moisture content = 23.5% dry basis, bed depth = 18 cm, air velocity = 2.9 m/s).

Fig. 15. Effect of air recirculation on energy consumption at different bed depths (initial moisture content = 33.3% dry basis, final moisture content = 23.5% dry basis, drying air temperature = 140°C, air velocity = 2.9 m/s).
4. Conclusions

1. The minimum fluidised bed velocity of dry soybean is 1.9 m/s. Page’s (1949) model with parameters in terms of first order polynomial depending on drying air temperature and specific airflow rate was found to predict the drying rate of soybean very well.

2. From the experimental results of fluidised bed drying, it could be concluded that the percentage of cracking and breakage of soybean increased with drying temperature and drying time. However, soybean drying at a temperature of 140°C did not increase the percentage of breakage to greater than the standard level of animal feed industry. A logistic equation describes the experimental results relatively well. It was found that soybean drying at high temperature (140°C) had no effect on protein quality. Urease activity was reduced to the standard value of the animal feed industry by using fluidisation, provided that the drying temperature was higher than 120°C.

Fig. 16. Effect of air recirculation on energy consumption at different drying air temperatures (initial moisture content = 33.3% dry basis, final moisture content = 23.5% dry basis, bed depth = 18 cm, air velocity = 2.9 m/s).

Fig. 17. Effect of air recirculation on drying cost at different bed depths (initial moisture content = 33.3% dry basis, final moisture content = 23.5% dry basis, drying air temperature = 140°C, air velocity = 2.9 m/s).
Simulation results showed that the optimal operating parameters for drying soybean by fluidisation were a drying air temperature of 140°C, a bed depth of 18 cm, a drying air velocity of 2.9 m/s and air recirculation of 90%. At these conditions, the percentages of cracking and breakage of soybean after drying were 27% and 1.7% respectively, the drying capacity was 4.65 t/h, the total primary energy consumption was 6.8 MJ/kg water evaporated (of which 15% was electricity for the fan and 85% was heat for the burner), and the drying cost was 2.38 Baht/kg water evaporated (US$ 0.06/kg water evaporated).

Acknowledgements

The authors would like to thank the Thailand Research Fund and the Australian Centre for International Agricultural Research for supporting this project. Thanks are also due to Saha Farm Co. Ltd for helping with the soybean quality analysis.

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