Penelitian/Research

MODELLING OF DRYING RATE OF CORN IN SPOUTED BEDS

Model Matematik Laju Pengeringan Jagung di dalam "Spouted Beds"

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Abstract - Studi ini dirancang untuk membentuk suatu model matematik ("two compartment model") yang dapat digunakan untuk menduga laju pengeringan jagung yang berlangsung terutama pada tahap laju pengeringan menurun dalam "spouted bed". Model matematik yang dikembangkan adalah fungsi dari kadar air awal jagung (Mo), suhu udara (T) serta kelembaban relatif (Rh) udara pengering. Model matematik yang merupakan fungsi dari Mo ternyata memberikan prediksi yang baik terhadap hasil empiris percobaan. Plot dari Mo terhadap waktu (t) baik menunut hasil model matematik maupun hasil empiris percobaan menunjukkan dua tahap laju pengeringan menurun.

INTRODUCTION

One of the many potential and innovative techniques in drying method is spouted bed drying. This method initially was developed as a method for drying wheat, finding that it was able to use much hotter air than in conventional wheat dryers without damaging the grain (MATHUR and EPSTEIN, 1955).

Recently several research have been conducted on the spouting phenomenon and the process has been adapted successfully in many commercial applications. The most popular application of spouted beds has been for drying of coarse, heat sensitive granular materials including agricultural products such as wheat, coffee, beans, peanuts, and corn. As regards the application of the dryer for corn, basic research is required involving measurement of the drying parameters. Consequently research into the application of spouted beds for drying of corn becomes a necessity. Only once the drying rates have been accurately modelled can the economics of drying by this method be evaluated.

This study was designed to describe the drying rate of corn in a spouted bed drying unit using a two (2) compartment model based on the initial moisture content (Mo) of the corn, and the inlet drying conditions i.e. temperature (T) and relative humidity of air (Rh). The specific objectives of this study were the following:

1) to fit a two compartment model to describe drying of corn in a spouted bed,
2) to verify the model suitable using the data.

Basically a spouted bed includes three main parts namely the spout, the annulus, and the fountain (fig.1). Granular particles are loaded into the column up to a level normally above the top of the conical region. In the drying process the air flowrate is increased gradually until a stable spout occurs. The particles are then entrained by the air spout up to the fountain region between the spout area and the column wall. The particles move downward and inward as a loosely packed moving bed, and the particle movement takes place in a cyclic manner (MATHUR and EPSTEIN, 1974).

DEVELOPMENT OF MATHEMATICAL MODEL

In this study, a two compartment model was developed to simulate the drying of corn, mainly in the falling rate period using a spouted bed dryer. The model is assumed as a form thin layer drying rate equation. The model serves to predict the average grain moisture content of corn being dried at exposure time of 40 - 90 minutes. Variable inputs to the inlet air temperature and humidity, and the mass flowrate. The program used in predicting the average moisture
content was written in QUICK BASIC 4.5, software developed by MICROSOFT. The model prediction were compared with experimental data.

Basic assumption

The assumption used to develop the mathematical model are the following:
(1) the bed behaves like a thin layer of grains;
(2) the bed remains well-mixed, since the spouted bed dryer could be considered as nearly a perfect mixer;
(3) the temperature and moisture content gradients within individual particles are negligible at any point in the bed and at any time;
(4) the initial moisture contents of the individual particles are uniform;
(5) the changes in ambient conditions of the air outside the bed were negligible for the duration of each experiment;
(6) the air leaving the annulus and the spout are at the same temperature;
(7) drying rate equation consists of two compartments;

Drying rate equation

Using the assumption that only the falling rate period of the grain need to be considered, a semi-theoretical drying equation was used. In this study, an equation representing the moisture ratio of corn was adopted and developed from the two compartment model proposed by SHARMA et al (1979), that is:

\[ MR = \frac{M - M_e}{M_o - M_e} = A_1 e^{-k_1 t} + A_2 e^{-k_2 t} \]  

\[ M = M_e + [M_o - M_e] (A_1 e^{-k_1 t} + A_2 e^{-k_2 t}) \]  

where, MR : the moisture ratio, 
A1 and A2 : the constants characteristics of the materials being dried, and 
K1 and K2 : the drying constants for the two respective compartments.

In this study the equation (3) was filled in order to obtain the values for A1, A2, K1, and K2 using a least squares and regression analysis, based on the data obtained from the ten drying experiments with varying initial moisture contents.

Equilibrium Moisture Content (Me)

The equation for determining Me was the equation obtained by a fit of the CHUNG-PFOS equation obtained as approved by The American Society of Agricultural Engineers (1984):

\[ M_e = E - F \ln \left[ \frac{1}{100} \ln (R_h/100) \right] \]  

\[ R_h = \exp \left[ -\frac{(A - C)(T + C)}{F(1 + C)} \right] \]  

where, E, F, C, A, and B are constants (E = 0.33872, F = 0.058970, C = 30.205, A = 312.80, and B = 16.958), here Rh is the relative humidity (%), M is the grain moisture content (decimal, dry basis), and T is temperature (°C).

Heat Losses

Due to the large exposed surface area of the chamber heat losses through the walls of the conical and cylinder (column) area were involved. It was assumed that the grain and air were at a constant uniform temperature 44°C, and the ambient air temperature was 21 °C. Basically the heat losses in the wall may be estimated using the equation:

\[ q = h A_s dT \]  

where, 

\[ h : \text{ heat transfer coefficient (a value of 5 W/m}^2\text{ was assumed),} \]
\[ A_s : \text{ approximate total surface area of conical and column area } (0.462 \text{ m}^2) \]
\[ dT : \text{ the difference in temperature between the grain and ambient air, } ^{0}C \]

After calculating it was found that the value of q was approximately 53 W for each run. This loss was taken into account in subsequent enthalpy calculations.

Estimating Exit Air Condition

Estimating exit air condition in terms of exit absolute humidity (He) was required since the value was used to estimate the mass flowrate. In this study exit absolute humidity was obtained by employing the inlet air enthalpy (h), the heat loss (q) and exit air temperature (T) with psychrometric chart:

\[ He = f(h, q, T) \]  

The inlet air enthalpy (h) was obtained by fitting the inlet Rh and inlet temperature. These values were measured by Rh and temperature probes which connected to the data logger. Heat loss (q) was calculated by equation (5). Exit air temperature was also measured by temperature probes connected to the data logger.

Moisture Removal Rate

The moisture removal rate was calculated from the difference between the moisture entering and moisture leaving the grain bed in the air as follow:

\[ m_w = m (He - Ha) \]  

where, 

\[ m : \text{ mass flowrate of air (kg/s) } \]
He: outlet air absolute humidity (kg H₂O/kg dry air)
Ha: inlet air absolute humidity (kg H₂O/kg dry air)
P: specific weight of air (kg/m³)
V: drying air velocity (m/s)
Aₜ: cross sectional area of inlet pipe where annubar placed (m²)

MATERIAL AND METHOD

Method

The Rh probes were introduced into the inlet orifice and founta section to measure the RH of the inlet and exhaust air (figure 2). Two thermocouples were installed to measure the temperature of the inlet and the exhaust air. The sensors were connected to the Datataker 100 Lab model data logger connected to an IBM-compatible computer, and data were recorded at one minute intervals.

The superficial air velocity was measured using a U tube water manometer, which was connected to the annubar after being calibrated using a set of rotameters. The air pressure was measured using a U tube manometer to obtain the specific weight of air. Two thermometers were used to measure the dry and wet bulb temperatures of the ambient air. A stop watch was used to control the drying time which was maintained at 40 minutes (former experiments) and 90 minutes (later experiments). The moisture content of the grain samples was determined using the oven method.

During each run samples were collected to determine the moisture content at 2 min, 5 min, 10 min, 20 min, and 40 min (for the 40 minutes total residence time runs) and at 2 min, 5 min, 10 min, 20 min, 40 min, 60 min, 80 min, and 90 min (for the 90 minutes residence time runs). Table 1 shows inlet air conditions including drying time, absolute humidity of the air, air temperature, and relative humidity of the air. Table 2 presents the experimental drying conditions including initial weight of corn, initial moisture content of corn, specific weight of air, air velocity, volumetric airflow, and mass flow rate.

Material

Drying experiments were conducted using wet corn (grain) with initial moisture contents of about 25 % wb, 24 % wb, 22 % wb, 21 % wb, and 19 % wb after conditioning from corn of 11.8 % wb. About fifty kilograms of rewetted corn was required for ten runs of the drying experiments. The physical properties of the corn are: specific weight: 1313.4 - 1284.5 kg/m³; 1299 kg/m³ (mean); mean diameter: 0.7257 x 10⁻² m; bulk density: 784.3 - 698.4 kg/m³; porosity: 38.5 - 47.20 %.

<table>
<thead>
<tr>
<th>Run</th>
<th>Time (min)</th>
<th>Abs. H (g/kg)</th>
<th>Temp (°C)</th>
<th>Rh (%)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>40</td>
<td>7.8</td>
<td>47.2</td>
<td>11.7</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
<td>10.3</td>
<td>47.2</td>
<td>15.4</td>
</tr>
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<td>3</td>
<td>40</td>
<td>10.2</td>
<td>47.6</td>
<td>15.0</td>
</tr>
<tr>
<td>4</td>
<td>40</td>
<td>11.4</td>
<td>46.7</td>
<td>18.1</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
<td>5.5</td>
<td>47.6</td>
<td>8.2</td>
</tr>
<tr>
<td>6</td>
<td>40</td>
<td>4.8</td>
<td>46.7</td>
<td>7.7</td>
</tr>
<tr>
<td>7</td>
<td>90</td>
<td>3.5</td>
<td>49.5</td>
<td>4.7</td>
</tr>
<tr>
<td>8</td>
<td>90</td>
<td>2.9</td>
<td>50.7</td>
<td>3.7</td>
</tr>
<tr>
<td>9</td>
<td>90</td>
<td>3.7</td>
<td>49.0</td>
<td>5.1</td>
</tr>
<tr>
<td>10</td>
<td>90</td>
<td>3.7</td>
<td>48.8</td>
<td>5.2</td>
</tr>
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Table 2. The experimental drying air conditions

<table>
<thead>
<tr>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
<th>(5)</th>
<th>(6)</th>
<th>(7)</th>
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<tr>
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<td>25.53</td>
<td>1.2255</td>
<td>16.75</td>
<td>3.183</td>
<td>3.90</td>
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<tr>
<td>3</td>
<td>5.250</td>
<td>20.89</td>
<td>1.2285</td>
<td>16.72</td>
<td>3.177</td>
<td>3.903</td>
</tr>
<tr>
<td>4</td>
<td>5.260</td>
<td>22.03</td>
<td>1.2376</td>
<td>16.14</td>
<td>3.076</td>
<td>3.796</td>
</tr>
<tr>
<td>5</td>
<td>4.683</td>
<td>24.74</td>
<td>1.2391</td>
<td>16.86</td>
<td>3.014</td>
<td>3.735</td>
</tr>
<tr>
<td>6</td>
<td>4.510</td>
<td>25.07</td>
<td>1.2391</td>
<td>16.58</td>
<td>2.960</td>
<td>3.668</td>
</tr>
<tr>
<td>7</td>
<td>4.700</td>
<td>24.74</td>
<td>1.2406</td>
<td>17.16</td>
<td>3.260</td>
<td>4.044</td>
</tr>
<tr>
<td>8</td>
<td>5.23</td>
<td>22.03</td>
<td>1.2406</td>
<td>16.91</td>
<td>3.213</td>
<td>3.986</td>
</tr>
<tr>
<td>9</td>
<td>5.20</td>
<td>19.85</td>
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<td>17.11</td>
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<td>20.02</td>
<td>1.2406</td>
<td>16.90</td>
<td>3.211</td>
<td>3.989</td>
</tr>
</tbody>
</table>

Where,
(1) : run number
(2) : initial weight of corn (kg)
(3) : initial moisture content of corn (% wet basis)
(4) : specific weight of air (kg/m³)
(5) : air velocity (m/sec)
(6) : volumetric airflow (l/min)
(7) : mass flow rate (kg/min).

RESULTS AND DISCUSSION

Result

The moisture content data from each run were used to determine the drying constants (k₁ and k₂) and the drying characteristics (A₁ and A₂) using an exponential curve fitting analysis program and statistical regression on the resulting parameters for each run. There were 7 datum points for the runs of 40 minutes total drying time and 10 for the runs of 90 minutes drying time.
After compiling the values of $A_1$, $A_2$, $k_1$, and $k_2$ for all experimental runs, these values were then analysed by multiple linear regression (CSS package) to formulate the final model. Table 3 below shows the values of the drying constants and the drying characteristics as well as the square of the correlation coefficient $r^2$ for each run.

<table>
<thead>
<tr>
<th>Run</th>
<th>$A_1$</th>
<th>$A_2$</th>
<th>$k_1$</th>
<th>$k_2$</th>
<th>$r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.125</td>
<td>0.647</td>
<td>0.872</td>
<td>0.0065</td>
<td>0.99</td>
</tr>
<tr>
<td>2</td>
<td>0.120</td>
<td>0.147</td>
<td>0.882</td>
<td>0.0040</td>
<td>0.99</td>
</tr>
<tr>
<td>3</td>
<td>0.119</td>
<td>0.359</td>
<td>0.879</td>
<td>0.0048</td>
<td>1.00</td>
</tr>
<tr>
<td>4</td>
<td>0.087</td>
<td>0.339</td>
<td>0.908</td>
<td>0.0066</td>
<td>1.00</td>
</tr>
<tr>
<td>5</td>
<td>0.073</td>
<td>0.445</td>
<td>0.925</td>
<td>0.0079</td>
<td>0.98</td>
</tr>
<tr>
<td>6</td>
<td>0.118</td>
<td>0.772</td>
<td>0.884</td>
<td>0.0062</td>
<td>0.98</td>
</tr>
<tr>
<td>7</td>
<td>0.171</td>
<td>0.551</td>
<td>0.827</td>
<td>0.0046</td>
<td>1.00</td>
</tr>
<tr>
<td>8</td>
<td>0.111</td>
<td>0.457</td>
<td>0.886</td>
<td>0.0044</td>
<td>1.00</td>
</tr>
<tr>
<td>9</td>
<td>0.100</td>
<td>0.229</td>
<td>0.900</td>
<td>0.0040</td>
<td>1.00</td>
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<tr>
<td>10</td>
<td>0.149</td>
<td>0.060</td>
<td>0.870</td>
<td>0.0029</td>
<td>1.00</td>
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</table>

The result showed that almost all the values of $r^2$ for the whole runs are one. This means that there was good explanation of the total variance in moisture by partial model for each run. The final drying characteristics, drying constants, and final two compartment model are as follow:

$$A_1 = 0.117$$
$$A_2 = 0.883$$
$$k_1 = -1.63 + 0.73 Mo$$
$$k_2 = -0.00284 + 0.00028 Mo$$
$$M = Me + (Me-Me)\left[0.117exp\left(-1.63 + 0.73 t\right) + 0.883exp\left(-0.00284 - 0.00028 Mo\right)\right]$$

where, $M \sim 0.27$ (M-Me) = 0.7% and $k_1$ and $k_2$ are significant at the 99 and 98% levels respectively.

At the start of this study, it was attempted to relate the drying constants and the drying characteristics as functions of not only Mo but also inlet air temperature (T) and Rh. The relations obtained are presented as follow:

$$A_1 = -0.171 + 0.00048 Mo + 0.00583 T - 0.00062 Rh, r^2 = 0$$
$$A_2 = 1.43 - \left(-0.00173 Mo\right) - 0.10 T - 0.0008 Rh, r^2 = 0.239$$
$$k_1 = 1.04 + 0.068 Mo - 0.050 T - 0.011 Rh, r^2 = 0.36$$
$$k_2 = 0.0062 + 0.00028 Mo - 0.00021 T - 0.000099 Rh, r^2 = 0.6$$

Although giving better predictions than the final model described in equation (10), this model was rejected as the grounds of significance of the coefficients.

To validate the accuracy of the final model, it was compared with the experimental moisture contents data. The comparison is presented graphically as a plot of moisture content (%, wb) versus time (minutes). In run 1, almost all of the experimental drying data were on the predicted curve (figure 3). The theoretical curves also showed close agreement with the experimental data for runs 2, 3, and 4 (figure 4). Good agreement was also displayed between moisture content profile for runs 5 and 6 and the final model curve (figure 5). The comparison between model curves and experimental data for runs 7, 8, 9, and 10 which are exhibited in figure 6 gave poor agreement.

**Discussion**

Plots of log the moisture content versus time showed that the data were situated on one of two straight lines. The first line falls rapidly from initial moisture content to an intermediate value, and the second falls more gradually (i.e. the value of M-Me tends towards zero). This means that the drying curves were found to contain two stages of falling rate period. These results support the assumption that the falling rate period was composed of two intervals of drying. These findings correspond with the results of investigations conducted by other researchers for analysis of thin layer drying rates of corn or other grains (SHARAF-ELDEN et al, 1980; HALL, 1980; SHARMA et al, 1982; TROGER and HUKILL, 1971; HALL and RODRIQUES-ARIAIS, 1958; CHEN and JOHNSON, 1969; MANIEZ and O'CALLAGHAN, 1971).

When comparing the final model drying rate with that of experimental results in the second line or second stages of the falling rate drying period, it was found that there was poor agreement especially for runs 7, 8, 9, and 10. In other words the second term of two compartment model obtained gave an inaccurate prediction.

Such disagreement may be due to several factors. Inherent experimental variability may lead to affect the curve fitting (as there is no physical analogy to either drying compartment). The lack of moisture equilibrium in the corn may also influence the disagreement due to the inadequate storage time after wetting). The variations in ambient conditions may also strongly affect the drying rate of corn during experiments. Since the air flowrate through the bed was not stable, it can have affected the drying rate of corn during experiments.
CONCLUSIONS AND RECOMMENDATIONS

It was found that the drying rates of corn consisted of two dominant straight lines in the ln (MR) versus time plots. This means that the drying curves were found to contain two stages of falling rate period possibly corresponding roughly to unsaturated surface drying (first falling period) and drying where the rate of water diffusion within the grain is slow and is the controlling factor (second falling period).

The two compartment model was found to be effective and sufficient to describe the experimental results of drying rate. The second compartment of the model becomes dominant during the second falling rate period.

This work is just a preliminary study and much works needs to be done such as:

(1) more experimental drying in spouted bed dryer is needed to better analyse the drying rate of corn with variation of bed height, air velocity, diameter of column and inlet nozzle, and cone angle (bed geometry). These data can be used to contribute semi-theoretical relation.

(2) further work is required to improve the two compartment model by involving the other meaningful input such as air temperature and relative humidity, so the revision model can be employed to fit the actual conditions in the test of spouted bed dryer.

ACKNOWLEDGEMENT

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I would also like to thank the Faculty workshop, and Department of Chemical Engineering of The University of New South Wales for their assistance during the study.

Figure 1. Schematic diagram of a spouted bed (MATHUR, 1974)
Figure 2. The layout of the spouted bed drying experiment

1 Fan
2 Valve
3 Straightener
4 Air Heater
5 Thermocouple
6 Datalogger Computer
7 Cyclone
Figure 3. The comparison between moisture content of the model and experimental results for run 1.

Figure 4. The comparison between moisture content of the model and experimental results for runs 2, 3, and 4.
Figure 5. The comparison between moisture content of the model and experimental results for runs 5 and 6.

Figure 6. The comparison between moisture content of the model and experimental results for runs 7, 8, 9, and 10.
REFERENCES


