# Modelling of seed drying in fluidised and spouted bed dryers

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Abstract

Drying experiments were conducted in the fluidised bed dryer (FBD) and spouted bed dryer (SBD) at temperature 40-80°C using maize, rice and wheat seed samples. The experimental data were fitted into four thin-layer drying models by least square method. As a result, Page's model and two-compartment model were the best-fitted models. Due to the limitation of these models, Page's model and the two-compartment model were modified by adding the drying temperature term. Subsequently, these models could efficiently predict the drying curves under a wider range of temperatures with root mean square (RMS) of the $MR_{predicted}$ - $MR_{measured}$ not over 0.035.

Keywords: Drying model, Seed drying, Fluidised bed dryer, Spouted bed dryer, Drying air temperature

## *1. Introduction*

To date, a number of drying models have been developed to estimate drying times. Several studies proposed simplified models for predicting the drying time of various products. Quite often, a semi-empirical relationship, so-called "thin layer" equation that is analogous to Newton's law of cooling, was introduced to obtain the drying rate of food grains (Soponronnarit, 1997).

Initially, a thin-layer drying model was proposed by Lewis (1921). Regularly, Lewis's equation is referred to as the exponential model and is used for modelling the drying rate of biological materials, especially food grains (Ghaly and Sutherland, 1984; Byler et al., 1987; Shei and Chen, 1998). After Lewis's work, several thin-layer drying models have been developed for food materials (See summary in Table 1). Some researchers (Byler et al., 1987; Shivhare et al., 2000; Tan et al., 2001) claimed that Page's model could predict the drying behaviour of biological materials more accurately than the exponential model, and the relationship between the drying rate constant and air temperature could be represented by the Arrhenius law.

Another thin-layer drying model that has been widely used for modelling the drying of food grain is the 'two-compartment model'. It was found appropriate for application to paddy drying (Sharma et al., 1982; Noomhorm and Verma, 1986). Due to the uniformity of moisture and temperature of samples in FBD and SBD resembling the samples in thin-layer dryer, in this work, a number of thin-layer drying models were developed for maize, rice and wheat seeds dried in FBD and SBD. The aim of this research was to develop thin-layer drying models for predicting the drying curves of maize, rice and wheat seeds in FBD and SBD. These models were expected to be useful for the drying industry.

## *2. Materials and methods*

### *2.1. Conditioning of seed samples*

Australian paddy variety "Amaroo", wheat variety "Westonia", and waxy maize variety "33A63" were used in the experiments. These raw seed samples had moisture contents lower than the designed levels for drying experiments, therefore, seeds were rewetted by adding a calculated amount of distilled water. Seeds were then mixed daily and kept at a temperature of 2-5°C for about 7 d to allow for mosuture equilibration within the seed and to avoid spoilage. The moisture content of seed samples was determined in accordance to ASAE standards (ASAE, 1988).

*2.2. Drying experiments*

Drying experiments were conducted in two types of dryers consisting of FBD and SBD as outlined in Table 1. During drying experiments, seed samples were collected in each time step for moisture content determination. The data of moisture content change of rice, maize and wheat seeds under each drying condition were used for the purpose of model development.

**Table 1** Summary of conditions used in drying experiments

| Drying method | Materials | Studied conditions | Remarks |
|---|---|---|---|
| Fluidised bed drying | Maize, rice and wheat seeds | Three levels of initial moisture content (20, 23, 25%wb) and three levels of temperature (40, 60, 80 °C). | Bed depth 0.1 m. Air velocity ≈ 2.8-3.0 m/s. The FBD was designed and constructed at the UNSW, Dept. Food Science & Technology. |
| Spouted bed drying | Rice and wheat seeds | Three levels of initial moisture content (20, 23, 25%wb) and three levels of temperature (40, 60, 80 °C). | Use sample amount equal to that used in FBD experiment. Air velocity ≈ 8-10 m/s. SBD and its accessories were designed and constructed at the UNSW, Dept. Food Science & Technology. |

*2.3. Drying model development*

Data from drying experiments were fitted into four thin-layer drying models, consisting of Page's model, two-compartment model, Wang and Singh's (1978) model and exponential model (see Table 2) by least square method. The software Statistica 5.5 StatSoft™ (StatSoft Inc., Tulsa, OK, USA) was used for model fitting. In developing thin-layer drying models, the required data consisted of initial moisture content, seed moisture content during drying process, seed equilibrium moisture content, temperature and relative humidity of drying air, and drying time. Equilibrium moisture contents were calculated by using the equations in Table 3 while the other data were obtained from the experiments.

**Table 2** List of thin-layer drying models used in this study

| Models | References |
|---|---|
| Lewis's model (Exponential model)<br>$MR = (M-M_e)/(M_i-M_e) = \exp(-kt)$ k = drying constant | Lewis, 1921; Ghaly and Sutherland, 1984; Shei and Chen, 1998 |
| Two-compartment model<br>$MR = (M-M_e)/(M_i-M_e) = Ae^{-k_1 t} + Be^{-k_2 t}$ A, B, $k_1$, $k_2$ = drying constants | Henderson, 1974; Sharaf-Elden et al., 1980 |
| Thompson's model<br>$t = A(\ln(MR)) + B(\ln(MR))^2$ A, B = drying constants | Thompson et al., 1968 |
| Page's model<br>$MR = (M-M_e)/(M_i-M_e) = \exp(-kt^N)$ k = f(air temp, air velocity) N = f(initial MC, RH) | ASAE, 1995; Sogi et al., 2003 |
| Wang and Singh's model<br>$MR = (M-M_e)/(M_i-M_e) = A\exp(-kt)$ A,k = drying constants | Wang and Singh, 1978 |

**Table 3** Equations used for estimating the equilibrium moisture content of seeds

| Product | Equations | References | Remarks |
|---|---|---|---|
| Maize | $M_e = \frac{1}{100}\left(\frac{\ln(1-RH)}{-0.00003074(T+273.15)}\right)^{\frac{1}{1.8166}}$ | Pudpong et al., 1990 | Where<br>$M_e$ = Equilibrium moisture content (db, decimal)<br>RH = Relative humidity of air, decimal<br>T =Inlet air temperature, °C |
| Rice | $M_e$= -- | Steffe and Singh, 1980 | |
| Wheat | $M_e$= -- | Bakker-Arkema et al., 1978 | |

*3. Results*

There were two major groups of drying models developed in this work namely models for FBD and those for SBD.

*3.1. Drying models for FBD*

Thin-layer drying models were developed for seeds of each of the three crops and each drying temperature. The coefficients of determination ($R^2$) and mean residual square (MRS) were calculated for each drying treatment and crop. The highest values of $R^2$ and the lowest of MRS were obtained for the Page's and two-compartment models. The results are shown in Tables 4 and 5. These models were not particularly useful because each could be used for one specified drying temperature.

**Table 4** Page's model for FBD

| Product | Drying air temperature (°C) | Page's model | $R^2$ | MRS |
|---|---|---|---|---|
| Maize | 40 | -- | 96.20 | 5.2E-04 |
| | 60 | -- | 98.10 | 4.7E-04 |
| | 80 | -- | 97.72 | 1.1E-03 |
| Rice | 40 | -- | 98.33 | 7.4E-04 |
| | 60 | -- | 99.40 | 3.9E-04 |
| | 80 | -- | 98.60 | 9.2E-04 |
| Wheat | 40 | -- | 98.85 | 5.7E-04 |
| | 60 | -- | 98.37 | 1.1E-03 |
| | 80 | -- | 98.31 | 1.2E-03 |

Table 5 Two-compartment model for FBD

| Product | Drying air temperature (°C) | Two compartment model | $R^2$ | MRS |
|---|---|---|---|---|
| Maize | 40 | -- | 95.14 | 6.6E-04 |
| | 60 | -- | 97.75 | 5.6E-04 |
| | 80 | -- | 96.91 | 1.4E-03 |
| Rice | 40 | -- | 98.44 | 7.0E-04 |
| | 60 | -- | 98.96 | 6.8E-04 |
| | 80 | -- | 99.09 | 6.0E-04 |
| Wheat | 40 | -- | 98.68 | 6.5E-04 |
| | 60 | -- | 98.66 | 8.6E-04 |
| | 80 | -- | 99.29 | 5.2E-04 |

Thus, two additional models were developed by modifying Page's and two-compartment models; a term for drying air temperature was added (Table 6). In fitting each modified model, the entire range of experimental data between 40 and 80°C drying air temperatures were used (Tables 7 and 8).

**Table 6** Modifications to Page's and modified two-compartment model

| Description | Equations | Remarks |
|---|---|---|
| Modified Pages model | $MR = (M-M_e)/(M_i-M_e)$<br>$= \exp(-kt^N \exp(-B/T_K))$ | Where<br>MR = Moisture ratio<br>M = Moisture content of sample at time t (db), decimal<br>$M_e$ = Equilibrium moisture content (db), decimal |
| Modified two-compartment model | $MR = (M-M_e)/(M_i-M_e)$<br>$= A_1 \exp(-k_1 t \exp(-B/T_K))$<br>$+A_2 \exp(-k_2 t \exp(-B/T_K))$ | $M_i$ = Initial moisture content of sample (db), decimal<br>$T_K$ = Drying air temperature (K)<br>t = Drying time (minutes)<br>k, $k_1$, $k_2$, $A_1$, $A_2$, B, N = Drying constants |

**Table 7** Modified Page's model for FBD

| Product | Drying air temperature (°C) | Modified Page's model | $R^2$ | MRS |
|---|---|---|---|---|
| Maize | 40-80 | -- | 98.07 | 6.9E-04 |
| Rice | 40-80 | -- | 98.57 | 9.4E-04 |
| Wheat | 40-80 | -- | 98.26 | 1.2E-03 |

**Table 8** Modified two-compartment model for FBD

| Product | Drying air temperature (°C) | Modified two-compartment model | $R^2$ | MRS |
|---|---|---|---|---|
| Maize | 40-80 | -- | 97.11 | 1.0E-03 |
| Rice | 40-80 | -- | 98.38 | 1.1E-03 |
| Wheat | 40-80 | -- | 98.75 | 8.8E-04 |

The comparison between the experimental data and the models for FBD (Page's, two-compartment, and modified Page's and modified two-compartment) is shown in Figure 1. There is a good agreement between the experimental and the model-predicted values for all models. Additionally, there is a slight improvement in the agreement between experimental and model predicted values for the modified models.

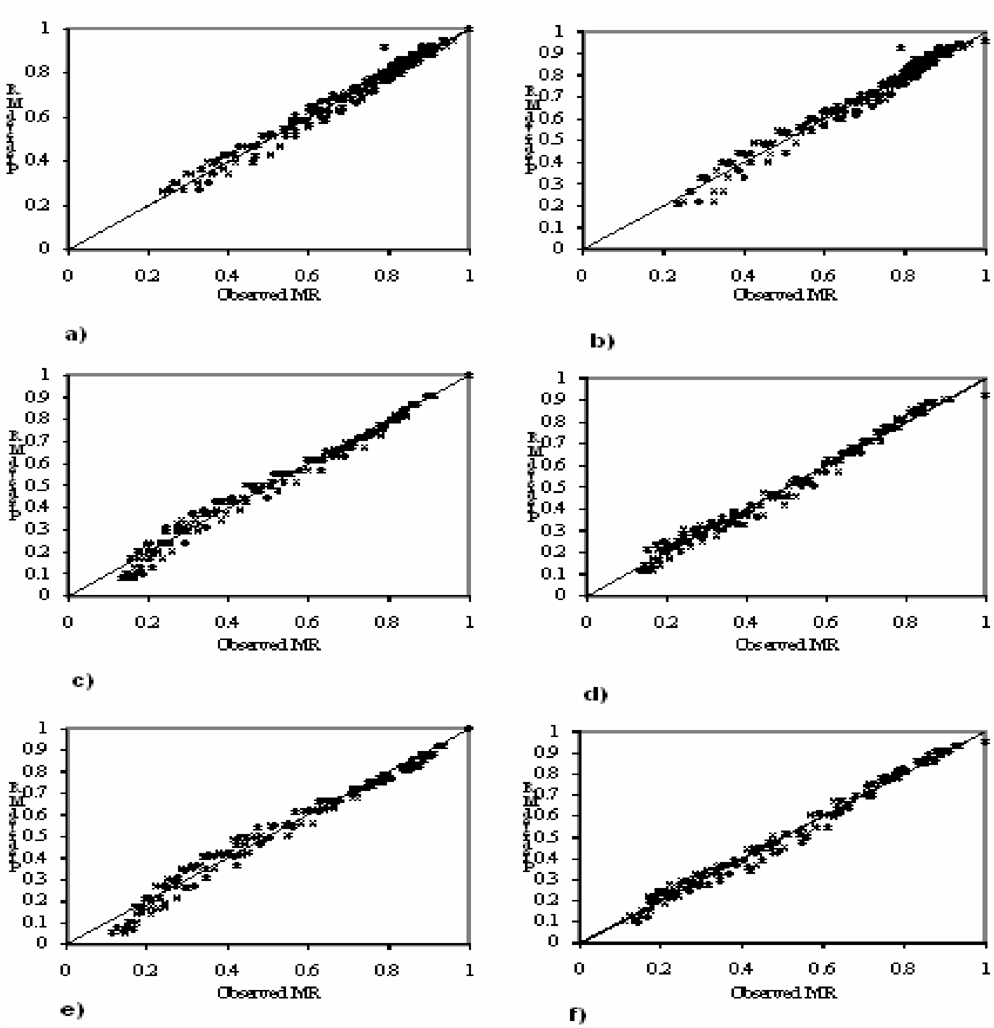


**Figure 1** Comparison between $MR_{observed}$ and $MR_{predicted}$ in FBD: a) Maize, modified Pages model b) Maize, modified two compartment model, c) Rice, modified Pages model d) Rice, modified two compartment model e) Wheat, modified Pages model f) Wheat, modified two compartment model

### *3.2. Drying models for SBD*

Best drying results of model fitting for both FBD and SBD were obtained using Page's and two-compartment model (Tables 9 and 10). As explained previously, these two models were modified to allow use over a wide range of drying air temperatures (between 40 and 80°C). The modified models are shown in Tables 11 and 12.

**Table 9** Page's models for SBD

| Product | Drying air temperature (°C) | Page's model | $R^2$ | MRS |
|---|---|---|---|---|
| | 40 | - | 98.97 | 3.4E-04 |
| Rice | 60 | - | 99.27 | 4.8E-04 |
| | 80 | - | 98.80 | 9.5E-04 |
| | 40 | - | 98.88 | 4.4E-04 |
| Wheat | 60 | - | 98.63 | 9.3E-04 |
| | 80 | - | 98.81 | 1.1E-03 |

**Table 10** Two compartment models for SBD

| Product | Drying air temperature (°C) | Two compartment model | $R^2$ | MRS |
|---|---|---|---|---|
| | 40 | - | 99.07 | 3.1E-04 |
| Rice | 60 | - | 99.42 | 3.8E-04 |
| | 80 | - | 99.68 | 2.5E-04 |
| | 40 | - | 98.92 | 4.3E-04 |
| Wheat | 60 | - | 98.84 | 7.9E-04 |
| | 80 | - | 99.62 | 3.5E-04 |

**Table 11** Modified Page's model for SBD

| Product | Drying air temperature (°C) | Modified Page's model | $R^2$ | MRS |
|---|---|---|---|---|
| Rice | 40-80 | - | 98.78 | 8.5E-04 |
| Wheat | 40-80 | - | 98.81 | 8.5E-04 |

Table 12 Modified two-compartment model for SBD

| Product | Drying air temperature (°C) | Modified two-compartment model | $R^2$ | MRS |
|---|---|---|---|---|
| Rice | 40-80 | - | 99.44 | 3.9E-04 |
| Wheat | 40-80 | - | 99.17 | 5.9E-04 |

The comparison between the experimental data and the models for SBD (Page's, two-compartment, and modified Page's and modified two-compartment) is shown in Figure 2. There is good agreement between the experimental and model-predicted values for all models with an overall better agreement for the modified models.

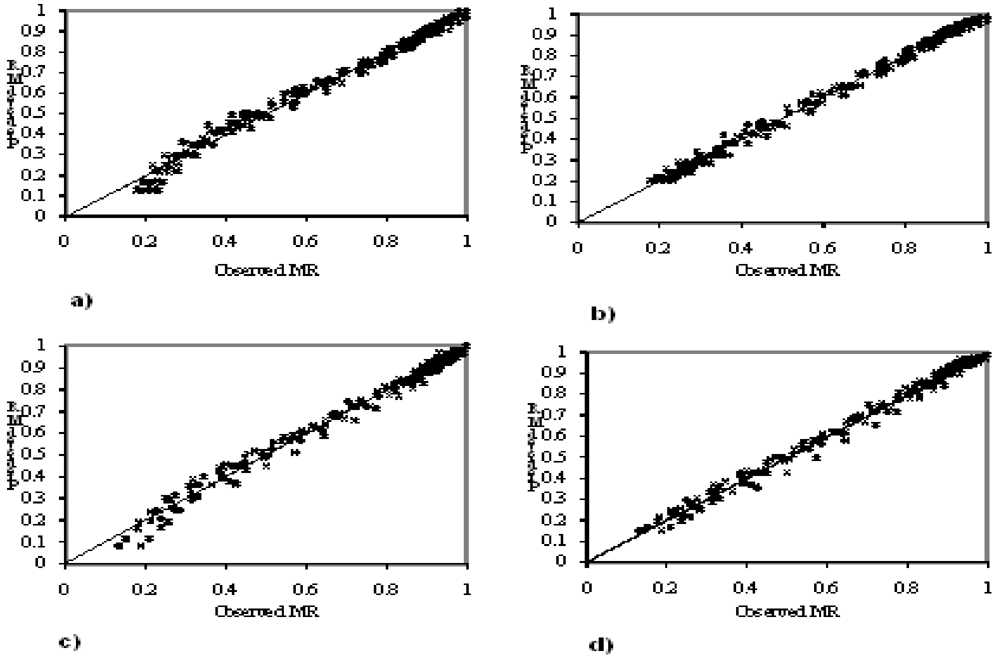


**Figure 2** Comparison between $MR_{observed}$ and $MR_{predicted}$ in SBD: a) Rice, modified Page's model ; b) Rice, modified two compartment model; c) Wheat, modified Page's model; d) Wheat, modified two compartment model

## *4. Discussion*

Based on the results of this study, the modified drying models for both types of dryers could accurately predict drying curves for maize, rice and wheat seed under a range of drying temperature from 40-80°C with the MRS values of deviations between predicted moisture ratio and the measured values ($MR_{predicted}$ - $MR_{measured}$) being ≤ 0.0012 (or RMS ≤ 0.035). Moreover, because these models were not complicated, users can use them on scientific calculators or personal computers.

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