Modelling thin layer microwave drying of soybeans

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Adu, B., Otten, L. and Brown, R.B. 1994. Modelling thin layer microwave drying of soybeans. Can. Agric. Eng. 36:135-141. The drying behaviour of thin layers of Natto soybeans exposed to different levels of microwave power at 2450 MHz was investigated using a single-mode (TE10) microwave apparatus designed and constructed to monitor instantaneous power absorption and mass loss during the drying process. Samples with initial moisture contents (IMC) from 24.6 to 15.2 % (dry basis) were each dried at absorbed powers of 0.76, 0.57, and 0.36 W/g. The drying rate of Natto soybeans decreased with decreasing absorbed power. For the same absorbed microwave power, the drying rate was the same for IMC of 22% and 24.6% but decreased with IMC below 22%. Soybean was found to be a hydro-diffusional simple material. The time-moisture shift technique was therefore used to develop drying master curves for the power levels investigated. A two-term semi-theoretical series solution of Fick’s equation described the drying behaviour over the entire drying period. Overall drying equations which predict the drying behaviour as a function of IMC, time, and absorbed power are presented.

Keywords: modelling, microwave, drying, thin layer, soybean

Introduction

Soybean (Glycine max L.) plays a very important role in our food system, both as a good quality oil seed and as a high protein feed, and soy oil has become a dominant high quality vegetable oil in the world (Snyder and Kwon 1987).

Soybean production in the United States alone was about 62 million tonnes in 1987 and has continued to grow (Snyder and Kwon 1987). However, seed quality deterioration resulting from unfavourable weather during the period of seed maturation remains a major concern of soybean producers. Seed moisture is about 40-50% dry basis (db) at the time maximum dry weight (physiological maturity) is attained. Under good weather conditions, seed moisture content could decrease to about 17% (db) in a week. On the other hand, matured soybeans left exposed to rain or damp weather develop a dark brown colour and a mealy or chalky texture, thus, affecting seed quality considerably, especially when seed moisture content is below 25%. To prevent deterioration under unfavourable weather conditions, soybeans are harvested at relatively high moisture contents while the weather is still good.

For safe storage, the moisture content must be reduced to about 13% (db). At present, the main available commercial form of soybean drying is with heated air. The maximum recommended temperature for heated air drying is 60°C, yet this temperature may yield seed splitting of about 40% (ASHRAE 1978). At higher temperatures, cracking and discoloration of the seed surface occur (Pinheiro Filho et al. 1982). Seed coat cracks affect soyoil quality and quantity, reduce storage life and germination potential, and the grading and pricing of the raw soybeans (McKenzie 1972; Pfost 1975). Consequently, heated air drying is avoided by growers whenever possible since seed coat cracking is claimed to be too excessive and too costly (Pinheiro Filho et al. 1982). Moreover, the low drying temperatures make heated air drying a slow process.

The problems of low drying rate and excessive cracking demand better drying methods. Higher drying rates, better product quality, and reduced potential of seed cracking during drying have been found to be some of the attributes of microwave drying (Decareau 1985). In addition, other soybean processing operations like the destruction of the antitrypsin growth inhibitor and the rupturing of the outer skin (seed coat or testa), a step needed for effective dehulling and further processing, are better achieved by microwave heating (Decareau 1985; Metaxas and Meredith 1983).

Otten and Levesque (1988) reported that at least two USA companies were continuing with the development of microwave dryers for agricultural products, however, economic constraints may restrict their use to the drying or processing of special crops. Soybean appears to be one such special crop. In addition, they stated that more research is required to determine the design parameters and operational conditions to make microwave drying of agricultural products more profitable.
Even though the heating mechanisms in heated air drying are different from those in microwave drying, the underlying transport process for moisture in both cases is diffusion. Semi-theoretical and empirical diffusion-based equations capable of predicting drying history already exist.

The objective of this study, therefore, was to determine the type of diffusion-based equation and the corresponding drying constants that accurately predict thin-layer microwave drying characteristics of soybeans.

LITERATURE REVIEW

Thin-layer drying
The drying rate of granular materials in a deep bed is based upon the drying rate of each seed within the bed and deep-bed drying can be modelled by considering the drying behaviour of a differential control volume or thin layer (Brooker et al. 1975).

The basic definition of a thin layer is one in which all seeds have the same moisture content and drying rate at any time in the drying process. This definition applies equally to microwave drying. The drying rate of any seed in the packed bed under microwave heating depends mainly on the power available to that particular seed. The percentage of power available to each seed in a packed bed depends on the penetration depth of the wave and the location of the kernel relative to the first kernel the wave encountered. Thus, the maximum thickness at which the power available to a kernel is not appreciably different from the power available to the first kernel the wave encounters, may be considered as the maximum thickness of the thin layer. Consequently, the maximum thickness of a thin layer can be specified as a specific fraction of the penetration depth of the wave for a particular material and (initial) moisture content.

A drying characteristic curve obtained from drying data may be mathematically described using diffusion-based semitheoretical or empirical drying equations. Semitheoretical thin-layer modelling involves statistically fitting a finite number of terms of a modified form of the infinite series solution of Fick's diffusion equation to the drying data (Sharaf-Elddeen et al. 1979). The semitheoretical equation may be given as:

\[ MR = A_0 \exp (-k_0 t) + A_1 \exp (-k_1 t) + \ldots \]  

where

- \( A_0, A_1 \) = characteristic constants (dimensionless),
- \( k_0, k_1 \) = drying constant (h\(^{-1}\)),
- \( MR = (M - M_e)/(M_0 - M_e) \) = moisture ratio (dimensionless), and
- \( t \) = drying time (h)

This form of the series solution of Fick's equation removes the restrictions presented by the material geometric shape, and represents the effect of the material shape and drying conditions in the form of drying constants.

MATERIALS AND METHODS

Apparatus and procedures
A single-mode (TE\(^{10}\)) experimental microwave apparatus was designed to measure drying variables. The experimental apparatus (Fig. 1) consisted of a test cavity made from a WR 430 waveguide modified to allow for uninterrupted measurement of drying material mass change. This was achieved by designing the weighing system in such a way that the sample container (made from Teflon) was supported by three Teflon pins (2.9 mm diameter) that passed through holes of 3.1 mm diameter at the bottom of the test chamber (Fig. 1b). The pins were attached to a platform that rested directly on a Mettler 2400 (Mettler Instrument Corporation, NJ) electronic balance. Thus, sample mass change was directly sensed by the balance. Readings of the balance were recorded at 2 min intervals by a computer connected to the digital output of the balance.

For the experimental conditions chosen, there was no cracking or burning of seeds, and seeds within a drying bed thickness of 40 mm were found to have the similar moisture content (same drying rate) at various stages of the drying process despite their location. Thus, any bed thickness less than 40 mm could be considered a thin layer. A bed thickness of 25 mm was chosen for the experiment.

The test sample container was a rectangular basket made of Teflon with dimensions of 106 X 54 X 30 mm. This left a clearance of about 1 mm between it and the waveguide walls. Air entered the test cavity through 2.9 mm diameter holes just before the test cavity. Moisture was removed via a duct connected by a flexible rubber hose to a pump (flow rate of 0.85 L/s).

Power absorbed within the test cavity was measured with two sets of bidirectional couplers fitted to each side of the test cavity. The power readings were continuously displayed and allowed the forward, reflected, and transmitted power to be continuously monitored.
A three-screw tuner was used to match the impedance of the workload (sample) to the characteristic impedance of the connecting waveguide. An oversized iron core dummy load (extreme left in Fig. 1) effectively absorbed all the transmitted power.

Following the bidirectional coupler on the right of the test chamber was a three-port circulator with one port serving to divert the reflected power back to an oversize dummy load. The other two ports connected the generator to the test cavity. The cover for the test cavity opening operated a switch that overrode the microwave generator 'on' switch so the generator switched off whenever the cover was open.

The apparatus was calibrated over the power range of interest by measuring the power lost or absorbed in the test chamber when the Teflon basket was empty. The calibration indicated that there was negligible power loss when the Teflon basket was the only load available. Thus, when drying the soybeans, any power losses in the test cavity could be attributed to power absorbed by the soybeans.

Sample preparation

The Natto variety of soybeans (Firstline Seed Limited, Guelph, ON), harvested at a moisture content around 28% db was used for the experiments. Natto is a special [(high protein (46.2%), low oil content (15.2%)] cultivar soybean bred purposely for human consumption. Samples were stored over saturated potassium chromate solution in a desiccator at 4°C for three weeks within which time the sample moisture content stabilized at 24.6% db. At 4 °C, the saturated potassium chromate solution provided a relative humidity of 96%. When the sample was kept at 20 °C, the moisture content stabilized at 22% db. Saturated potassium chromate solution produces an essentially constant relative humidity atmosphere which does not vary appreciably over small temperature ranges (Perry 1984).

Lower initial sample moisture contents were achieved by keeping the soybeans in an open pan and allowing them to lose moisture under ambient conditions. The sample was stirred at least six times every 24 h. Its moisture content was monitored from time to time until the required moisture content was reached. It was then sealed in an air-tight glass jar. This approach was used to achieve initial sample moisture contents of 18.7 and 15.2% (db). Seed coat cracking for the soybeans was observed for microwave absorbed power that exceeded 0.76 W/g. To prevent seed coat cracks, the maximum absorbed power of 0.76 W/g was chosen.

The four initial moisture contents were each subjected to specific power levels of 0.76, 0.57 and 0.36 W/g (dry matter). Sample sizes of about 100 g were used for each experimental run. Microwave power absorption at 2450 MHz has been found to be practically independent of the moisture content for moisture contents below the critical moisture content of the material (Metaxas and Meredith 1983). This is supported by data on dielectric loss factor for shelled, yellow-dented field corn published by Nelson (1978).

Drying procedure

A typical test included filling the Teflon basket with the seeds, tapping it gently to duplicate gravity packing, and placing it on the Teflon pins in the test cavity. The microwave cavity cover was then secured in place and the fan turned on for about 3 min to remove any available surface water before beginning the microwave drying. Each test was allowed to run until the moisture loss rate was about 0.05 g/min per kilogram of sample (dry basis). Preliminary studies show that sample moisture content was between 13.5 and 12% db when the moisture loss rate of the sample remained constant around 0.05 g/min per kilogram of sample. The final moisture content for the treatments was between 11.5 to 13% db, depending on power input. Drying data were recorded at 2 min intervals with three replicates for each test condition.

RESULTS AND DISCUSSION

Factory calibrated Marcon microwave power meters and associate sensors (Marconi 6950, Marconi Instruments, NJ) were used for power measurements. Heat and mass transfer data of distilled water heated with the apparatus were used to confirm the accuracy of absorbed power measurements.

The Statistical Analysis System (SAS 1986) was used for data analysis and model determination. Drying data recorded with the apparatus showed very little scattering (Fig. 2) and replicate results did not vary significantly from each other (Table I, Pr > F = 0.9637).

Plots of moisture content (MC) versus time data for the drying processes exhibited a decaying exponential trend for all absorbed powers used. The drying rates for a particular
initial moisture content (IMC) increased with increasing absorbed power. This result agrees with the results of other microwave grain drying studies (St. John and Otten 1989; Shivare 1991).

To establish the effect of initial moisture content (IMC) on drying rate moisture ratio (MR) versus time curves for the different IMC's but the same absorbed power treatment were plotted. Equilibrium moisture contents (EMC) under the selected drying conditions were computed by determining the moisture content for samples after they showed no further mass loss under a drying condition. The moisture content of the samples was determined by the ASAE oven method for soybeans (15g at 102 °C for 72 hours, ASAE 1991). Results of EMC tests indicated that for the microwave drying conditions chosen for the study, the EMC was effectively zero confirming earlier work done by St. John (1988) and Shivare (1991).

Moisture ratio versus time plots exhibited an exponential decay trend similar to those of the moisture content plots. For the same microwave absorbed power, plots of the moisture ratio versus time (Fig. 3) revealed that moisture ratio curves (MR) for IMC's below 22% [18.7 and 15.2%] (db) were quantitatively different from each other. The drying rates decreased with decreasing initial moisture content. The MR versus time curves for initial moisture contents of 24.6 and 22.0% were about the same for all power levels used, indicating that their microwave drying history does not depend on their initial moisture content.

Drying master curve and shift factor

Christensen (1971) showed that for many materials, the effect of moisture content or temperature on their time-dependent properties may be compensated for by horizontally shifting along the time axis. In essence, it is possible to express the effect of moisture content or temperature on a time dependent property behaviour as a function (extension or reduction) of process time in some materials. When such a possibility exists, curves for which the only variable is moisture content or temperature assume similar qualitative trends but are shifted horizontally along the abscissa when plotted on an appropriate time axis and will end up super imposed on each other to form a single “master curve” after shifting by appropriate factors. A material for which the effect of moisture content or temperature can be accounted for by a function of process time is characterised as a simple material in the context of the process or phenomenon taking place. For example, the effect of temperature or moisture content on the stress relaxation modulus of biomaterials that have undergone rapid straining has been accounted for conveniently as time functions by researchers in the field of rheological studies (Herum et al. 1979). Within the context of rheology, the material has been described as thermo-hydro rheologically simple. In diffusion based drying situations, therefore, if the effect of IMC could be accounted for by a function of process-time, the material may be classified as a hydro-diffusively simple material.

The relationship between moisture content and process time during drying has been found to be exponential within the falling rate period of drying. In situations where the relationship between moisture content and time is exponential, the function of the time, \( t_m \), that may be used to compensate for the effect of moisture content is found to be logarithmic (Herum et al. 1979). Consequently, a semi-log plot of the drying characteristics curves for different initial moisture contents produces curves with a linear relationship between MC or MR and ln (time). These curves were used to compute the shift factors required to super impose all IMC curves on each other to obtain a single master curve (Mensah et al. 1984; Lui et al. 1989).

Moisture ratio (MR) versus time plotted on a semi-log scale for the same absorbed power but different initial moisture content resulted in curves of similar shape but shifted along the time abscissa (Fig. 4). This indicates that the effect of IMC on drying rate during microwave drying could be expressed as an increase or decrease in drying time and a soybean seed may be classified as a hydro-diffusively simple material.

Preliminary analysis showed that the effect of experimental error introduces minor deviations among the curves (Fig. 4) in relation to their gradients at certain similar moisture ratio points. Consequently, different IMC curves when used as reference curves to compute the shift factors needed to superimpose the IMC curves on each other, provided different degrees of deviation or spread about the reference curve chosen. The 18.7% IMC curve provided the least degree of spread and hence the best master curves for the power level chosen. It was therefore chosen as the reference curve for determining the moisture shift factors.

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**Table I: Analysis of variance for test replicate data of apparatus**

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>Sum of squares</th>
<th>Mean square</th>
<th>f-ratio</th>
<th>P &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment</td>
<td>3</td>
<td>3690.99</td>
<td>1230.33</td>
<td>0.39</td>
<td>0.9637</td>
</tr>
<tr>
<td>Error</td>
<td>67</td>
<td>211364.56</td>
<td>3154.69</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>70</td>
<td>215055.55</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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**Fig. 3.** A typical graph showing the influence of Initial Moisture Content (IMC) on drying rate.
Fig. 4. A typical semi-log plot of Moisture Ratio (MR) versus time data of the Initial Moisture Contents used.

Table II: Time shift factors, $a_m$, for absorbed power levels and IMC's used

<table>
<thead>
<tr>
<th>Initial moisture content %</th>
<th>Microwave power absorbed (W/g) db</th>
<th>Mean time shift factor, $a_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.76</td>
<td>0.57</td>
</tr>
<tr>
<td>24.6</td>
<td>1.428</td>
<td>1.516</td>
</tr>
<tr>
<td>22.0</td>
<td>1.433</td>
<td>1.521</td>
</tr>
<tr>
<td>18.7</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>15.2</td>
<td>0.531</td>
<td>0.468</td>
</tr>
</tbody>
</table>

abscissa range covered by the curves and the reference curve determined the horizontal axis along which the shift factors were to be computed. A shift factor was determined by computing the degree of shift of a point along this horizontal axis from a similar MR point on the reference curve. Table II shows the time-moisture shift factors ($a_m$) that provided the best drying-master curve for each power level. Figure 5 shows a typical result after shifting has been effected.

The nonlinear regression (NLIN) procedure in SAS (1986) was used to model the relationship between initial moisture content (IMC) and the shift factor ($a_m$). The resulting equation (Eq. 2) predicts time shift factors with an $R^2 = 0.9979$

$$a_m = 1.076 + 0.1347 (IMC - 18.7) - 0.0096 (IMC - 18.7)^2$$

The model predictions was used to determine the drying master curve for the microwave powers used.

Modelling drying behaviour

The possibility of using a one-term exponential model and the Page model was examined. Both models failed to provide good predictions of drying behaviour. For example, the Page model showed drying rates that were too high at the initial and later stages of drying, but too low in between (Fig. 6). The two-term diffusion-based semitheoretical model provided a good fit ($R^2 > 0.9965$) for the three master curves representing the three absorbed power levels investigated. Table III gives the drying constants for each power investigated. The set of equations (Eqs. 3-6) predicts thin-layer drying behaviour of Natto soybean as a function of time, initial moisture content, and absorbed power:

$$MR = A \exp^{k a_m} + (A - 1) \exp^{k B a_m}$$

where $a_m$ is given by Eq. 2;

$$k = 0.03242 P + 0.0039$$

$$A = 0.281 P + 0.1585$$

$$k B = 0.0042 - 0.128 P + 0.0983 P^2$$

where $A$, $K$, $B$ = drying constants, and $P$ = absorbed microwave power (W/g).

Shivare et al. (1993) have independently confirmed the accuracy of the data. They also confirmed studies that diffusion-based models predict thin-layer microwave drying characteristics of seeds. Figure 7 shows a typical drying
Table III: Drying constants corresponding to absorbed power levels used

<table>
<thead>
<tr>
<th>Absorbed power (W/g)</th>
<th>Drying constants</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>k</td>
</tr>
<tr>
<td>0.76</td>
<td>0.030415</td>
</tr>
<tr>
<td>0.57</td>
<td>0.022496</td>
</tr>
<tr>
<td>0.36</td>
<td>0.016675</td>
</tr>
</tbody>
</table>

2. There appears to be a critical moisture content above which the rate of moisture loss of soybean under microwave drying is not affected by the initial moisture content. The critical moisture content (IMCC) appears to be around 22% dry basis.

3. The effect of initial moisture content on microwave drying rates of soybeans can be expressed as an extension or reduction in drying time. Thus, under microwave drying conditions, soybeans are a hydro-diffusionally-simple material.

4. The two-term approximation of the semitheoretical general series solution of Fick's diffusion equation predicts thin-layer microwave drying characteristics of Natto soybean over the entire drying period.

**REFERENCES**


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