Brazilian Journal
of Chemical
Engineering

ISSN 0104-6632
Printed in Brazil
www.abeq.org.br/bjche

Vol. 34, No. 01, pp. 143 - 158, January - March, 2017
dx.doi.org/10.1590/0104-6632.20170341s20150509

# QUALITY, PERFORMANCE ANALYSIS, MASS TRANSFER PARAMETERS AND MODELING OF DRYING KINETICS OF SOYBEAN

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*(Submitted: August 15, 2015 ; Revised: November 5, 2015 ; Accepted: December 22, 2015)*

**Abstract -** Different aspects of soybean drying such as energy and exergy analyses, quality, mass transfer parameters, and modeling of drying kinetics were investigated in a microwave dryer. Results showed that energy and exergy efficiency increased with increasing microwave power, while values of energy efficiency (33.70 to 66.0%) were higher than exergy efficiency (23.38 – 48.30%). Specific energy consumption and energy loss varied 4.93 to 9.11 MJ/kg water and 5.04 to 8.89 MJ/kg water, respectively. Approximately 8.94 to 20.07% of the total energy input is consumed by increasing of the product temperature. The values of improvement potential changed between 1.31- 5.35 MJ/kg water. Bulk density, degree of shrinkage and rehydration ratio varied from 726.6 to 762.8 kg/m$^3$, 0.888 to 0.910, and 0.618 – 0.799, respectively. Parameters total color change (14.68 - 19. 89) and hue angle (88.07 to 91.73°) increased with increasing microwave power. Effective diffusivity and mass transfer coefficient varied from $1.99\times10^{-9}$ to $12.25\times10^{-9}$ m$^2$/s and $2.71\times10^{-6}$ to $19.98\times10^{-6}$ m/s, respectively. The activation energy was found to be 4.98 W/g for a diffusion model and 5.33 W/g for a mass transfer model. Among the models, the Page model was found to best describe the drying behavior of soybean.

*Keywords*: Soybean, Quality; Energy consumption; Exergy efficiency; Drying.

## INTRODUCTION

Soybeans are harvested typically at moisture contents in the range 25-33% wet basis. But for safe storage, it is necessary to have a moisture content of soybeans less than 10% wet basis according to the local climate conditions (Darvishi *et al.*, 2014a). Also, raw soybean cannot be consumed as human food or animal feed because of the presence of anti-nutritional substances, some of which may harm the consumer. In the treatment of raw soybeans after harvest, several methods are available such as cooking, roasting and drying (Gowen *et al.*, 2008; Dondee *et al.*, 2011; Pfeifer *et al.*, 2010).

The drying kinetics of food is a complex phenomenon and requires simple representations to predict the drying behavior, and for optimizing the drying parameters. Knowledge of both the moisture diffusivities and mass transfer coefficients for the various systems is essential, as more complex mathematical models and correlations which can provide a more in-depth understanding of the drying operations require data on specific mass transfer parameters (McMinn *et al.*, 2003). The moisture diffusion of a food material characterizes its intrinsic mass transport property of moisture, which includes molecular diffusion, liquid diffusion, vapour diffusion, surface diffusion, capillary flow, hydrodynamic flow and other

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*To whom correspondence should be addressed possible mass transport mechanisms (Pathare and Sharma, 2006; Aboltins, 2013; Celma *et al*., 2012).

Drying is the most energy intensive process in the food industry. Therefore, improving drying processes by reducing energy consumption and providing high quality with minimal increase in economic input has become the goal of modern drying (Doymaz, 2011; Darvishi *et al*., 2014a; Alibas, 2007). In recent years, thermodynamic analyses, particularly exergy analyses, have appeared to be an essential tool for the system design, analyses and the optimization of thermal systems. From the thermodynamics point of view, exergy is defined as the maximum amount of work that can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference environment (Akpinar *et al*., 2006, Prommas *et al*., 2012).

Convective drying in hot air is still the most popular method applied to reduce the moisture content of fruits and vegetables. Nevertheless, this method has a number of disadvantages such as very long-lasting drying period, high energy consumption, contamination problems, low energy efficiency and high costs, which is not a desirable situation for the food industry (Alibas, 2007; Ozbek and Dadali, 2007, Al-Harahsheh *et al*., 2009). The desire to reduce the above problems, as well as to achieve a fast and effective thermal process led to the use of microwave and dielectric heating methods for food drying (Bondaruk *et al*., 2007; Orsat *et al*., 2007). Microwave drying has several advantages such as higher drying rate, shorter drying time, decreased energy consumption, and better quality of the dried products (Sarimeseli *et al*., 2011; Wang *et al*., 2007; Soysal *et al*., 2006).

Therefore, the objectives of this work were to (1) present energy and exergy analyses of microwave drying of soybean, (2) estimate the improvement potential of the microwave drying process, (3) calculate mass transfer parameters (moisture diffusivity, mass transfer coefficient, activation energy for diffusion and mass transfer models), (4) determine of the quality aspects (rehydration ratio, shrinkage, colour), and (5) to fit the experimental data to six thin-layer drying models and estimate the constants.

## MATERIALS AND METHODS

### Sample Preparation

Fresh soybean seeds used for the drying experiments were obtained from the Gorgan region of Iran. The soybean samples were cleaned in an air screen to remove all foreign material (dust, dirt, broken seeds) and stored at 4±0.5 °C before they were used in experiments. Soybean seeds had an initial moisture content of 24.5±0.2% wet basis (0.325±0.003 kg water kg dry matter), which was determined by oven drying at 103 ºC for 24 h (Darvishi *et al*., 2014b).

### Drying Details

The schematic diagram of the experimental apparatus is shown in Figure 1. Drying studies were carried out with a domestic digital microwave oven (M945, Samsung Electronics Ins) with the technical feature of 230 V, 50 Hz and 1000 W. The oven is fitted with a controller to adjust the microwave output power and the time of processing. The dimensions of the inner cavity are 327×370×207 mm. The oven has a fan for air flow in the drying chamber and cooling of the magnetron. The moisture from the drying chamber was removed with this fan by passing it through the openings on the right side of the oven wall to the outer atmosphere.

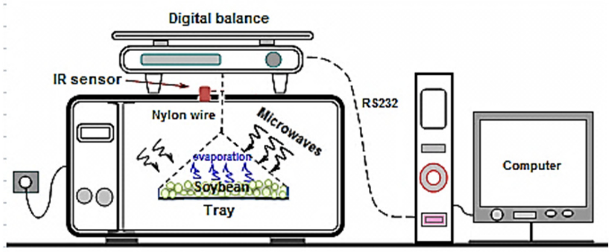

**Figure 1:** Schematic diagram of the experimental apparatus.

A digital analytical balance (GF-600, A & D, Japan) with accuracy of ±0.01 g was positioned on the top of the microwave oven for mass determination at an interval of 15 s. A sample tray in the microwave oven chamber was suspended on the balance with a nylon wire through a ventilation hole in the center of the chamber ceiling. About 105 g of the prepared samples were uniformly spread in a thin layer (thickness of layer ≈ 2 cm) on the tray and dried to around 0.1291±0.009 moisture content (kg water/kg dry matter). The moisture content calculation was based on the following equation (Usub *et al*., 2010):

$$M_t = \left( \frac{(1+M_0)\times m_0}{m_t} - 1 \right) \tag{1}$$

Temperature of sample was measured by IR temperature sensor (accuracy of ±1.5 ºC). At each drying microwave power, the experiments were replicated three times and the average values were used. The reference dead state conditions were considered as $T_0 = 20$ ºC and $P_0 = 101.325$ kPa.

## Energy Analyses

The energy conservation of the sensible heat, latent heat and source heat of microwave is written as (Jindarat *et al.*, 2011):

$$\overbrace{P_{in}\times t}^{\text{energy input}} = \overbrace{\left(\overbrace{(mC_pT)_{dp}}^{\text{energy of dry product}} - \overbrace{(mC_pT)_{wp}}^{\text{energy of wet product}}\right) + \overbrace{\lambda_{wp}m_w}^{\text{latent heat}}}^{\cong\ \text{energy absorption}} + \overbrace{E_{ref} + E_{tra}}^{\cong\ \text{energy loss}} \tag{2}$$

Thermal drying efficiency is defined as the heat used to evaporate moisture from the samples divided by the heat input from the microwave source (Soysal *et al.*, 2006):

$$\eta_{en} = \frac{\text{energy absorption}}{P_{in}\times t} \tag{3}$$

Specific heat capacity and latent heat of the sample were calculated according to the following equations (Hall, 1975; Sharqawy *et al.*, 2010; Azadbakht *et al.*, 2013; da Silve *et al.*, 2012):

$$C_p = 1.379 + 0.032M \qquad M \le 30.5\%\ \text{w.b.} \tag{4}$$

$$\frac{\lambda_{wp}}{\lambda_{fw}} = 1 + 23\exp(-40M_t) \tag{5}$$

$$\lambda_{fw} = 2503 - 2.386T \tag{6}$$

where $\lambda_w$ is obtained in kJ/kg when the temperaure is given in ºC. The specific energy loss is determined by (Darvishi *et al.*, 2014a):

$$E_{loss} = (1-\eta_{en})\times\frac{P_{in}\times t}{m_w} \tag{7}$$

The energy consumed for drying a kilogram of samples is calculated using Eq. (8):

$$E_{sc} = \frac{P_{in}\times t}{m_w} \tag{8}$$

## Exergy Analyses

The general exergy balance in the drying chamber was expressed as follows:

$$\overbrace{P_{in}\times t}^{\text{energy input}} = \overbrace{\left(\overbrace{(m\times ex)_{dp}}^{\text{exergy of dry product}} - \overbrace{(m\times ex)_{wp}}^{\text{exergy of wet product}}\right) + ex_{evap}\times t}^{\text{exergy absorption}} + \overbrace{EX_{ref} + EX_{tra}}^{\cong\ EX_{loss}} \tag{9}$$

The rate of exergy transfer due to evaporation in the drying chamber was (Icier *et al.*, 2008):

$$ex_{evap} = \left(1 - \frac{T_0}{T_p}\right)\times \dot{m}_w\lambda_{wp} \tag{10}$$

The specific exergy of wet or dry product was determined using Eq. (11) as follows (Akpinar *et al.*, 2006):

$$ex = C_p\left[(T-T_0) - T_0\ln\left(\frac{T}{T_0}\right)\right] \tag{11}$$

The exergy efficiency of the dryer can be defined as the ratio of exergy output to exergy input, where the product is only the rate of exergy evaporation process and the electrical power is the rate of exergy input to the drying chamber. The exergy efficiency for any drying system is the ratio of exergy use (investment) in the drying of the product to exergy of the drying source supplied to the system (Dincer and Sahin, 2004):

$$\eta_{ex} = \frac{EX_{evap}}{P_{in}} \tag{12}$$

Exergy loss is determined by Eq. (13):

$$EX_{loss} = EX_{in} - EX_{out} \tag{13}$$

The rate form as given by Hammond and Stapleton (2001) was used to determine the exergetic improvement potential of the drying process. The exergetic improvement potential is expressed as:

$$IP = (1-\eta_{ex})(EX_{in} - EX_{out}) \tag{14}$$

## Quality Aspects

### Rehydration Ratio

Dried soybean seeds (5 g) were rehydrated at 25 ºC for 2 h by being immersed in 60 mL of distilled water. The rehydration ratio was described by:

$$Rr = \frac{m_l - m_d}{m_l} \qquad (15)$$

### Colour Measurement

L (lightness), a (redness), b (yellowness) colour values of the fresh and dehydrated products were measured using a spectral photometer before and after drying. Total colour change and hue angle were calculated as follows:

$$\Delta E = ((L_d^* - L_f^*)^2 + (a_d^* - a_f^*)^2 + (b_d^* - b_f^*)^2)^{\frac{1}{2}} \qquad (16)$$

$$h = \tan^{-1}\left(\frac{b}{a}\right) \qquad (17)$$

### Shrinkage

Shrinkage of bulk soybean is often represented by:

$$Sh = \left(\frac{V_d}{V_0}\right) \qquad (18)$$

The bulk density is the ratio of the mass of a sample of a seed to its total volume and it was determined by filling the seeds in a cylinder of known volume (30 mm diameter and 60 mm height) and weighing on an electronic balance.

$$\rho_b = \frac{m}{V_c} \qquad (19)$$

### Drying Kinetics and Modeling

The change of moisture in soybean seeds during drying was expressed as the moisture ratio defined as:

$$MR = \left(\frac{M_t - M_e}{M_0 - M_e}\right) \qquad (20)$$

The values of $M_e$ are relatively small compared to $M_t$ and $M_0$ (especially for microwave drying), hence the error involved in the simplification by assuming that $M_e$ is equal to zero is negligible. Six well-known thin-layer drying models in Table 1 were tested to select the best model for describing the drying curve of the soybean seeds. The non-linear regression analysis was performed using the SPSS.18 program and Microsoft Office 2003 Excel. Reduced chi-square ($\chi^2$), root mean square error (RMSE) and the coefficient of determination ($R^2$) were used as the primary criteria to select the best equation to account for variation in the drying curves of the dried samples. These parameters can be calculated as follows:

$$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{pre,j} - MR_{exp,i})^2}{N - z} \qquad (21)$$

$$RMSE = \left(\frac{\sum_{i=1}^{N}(MR_{pre,j} - MR_{exp,i})^2}{N}\right)^{0.5} \qquad (22)$$

**Table 1: Mathematical models given by various authors for the drying curves.**

| Model name | Model | References |
|---|---|---|
| Henderson and Pabis | MR = a exp (- kt) | Darvishi *et al.* (2014a) |
| Newton | MR = exp (- kt) | Wang *et al.* (2007) |
| Wang and Singh | MR = 1 +bt + at$^2$ | Sarimeseli (2011) |
| Page | MR = exp (- kt$^n$) | Lee and Kim (2009) |
| Logarithmic | MR = a exp (- kt) + b | Kingsly *et al.* (2007) |
| Midilli | MR = a exp (- kt$^n$) + bt | Midilli *et al.* (2002) |

where k is the drying constant (1/min) and a, b, n are equation constants

## Mass Transfer Parameters

### Moisture Diffusivity

The Fick's diffusion equation developed for solid objects with spherical geometry by Crank (1975) was applied to the experimental data on the assumption that there is a uniform initial moisture distribution and negligible external resistance. The equation is in the form (Duc *et al.*, 2011):

$$MR = \frac{6}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{n^2}\exp\left(-n^2\pi^2\frac{D_{em}}{r^2}t\right) \qquad (23)$$

Simplifying by taking the first term of the series solution:

$$MR = \frac{6}{\pi^2}\exp\left(-\pi^2\frac{D_{em}}{r^2}t\right) \qquad (24)$$

Effective diffusivity is also typically calculated by using the slope of Eq. (24), namely, when a natural logarithm of MR versus time was plotted, a straight line was obtained with a slope of $\pi^2 \frac{D_{em}}{r^2}$.

### Mass Transfer Coefficient

Kaya *et al.* (2010) described a procedure to determine the mass transfer coefficient as follow:

$$hm = -\frac{V_p}{A_p \times t} \ln(MR) \tag{25}$$

For a symmetrically heated sphere, V/A is equal to the radius (Torki‑Harchegani *et al.*, 2014), hence for the soybean seeds Eq. (25) can be simplified to:

$$h_m = -\frac{r}{t} \ln(MR) \tag{26}$$

Due to variation of time and Ln(MR) during the process, the average value of $h_m$ along the whole moisture content profile was calculated using the following expression:

$$h_{m-av} = -\frac{\int_{M_{initial}}^{M_{final}} h_m(M)dM}{\int_{M_{initial}}^{M_{final}} dM} \tag{27}$$

### Activation Energy

In this study, the Arrhenius equation was used in a modified form to illustrate the relationship between moisture diffusivity, mass transfer coefficient and ratio of the microwave output power density to sample amount instead of the temperature for calculation of the activation energy as the temperature is not a measurable variable in the standard microwave oven used for the drying process (Raquel *et al.*, 2012; Torki‑Harchegani *et al.*, 2014).

$$D_m = D_0 \exp\left(\frac{E_{ad}\, m_o}{P}\right) \tag{28}$$

$$h_{m-av} = h_0 \exp\left(-\frac{E_{am}\, m_o}{P}\right) \tag{29}$$

### Experimental Uncertainty

Errors and uncertainties in the experiments can result from the environmental conditions, instrument selection, reading, calibration etc. In the present study, temperatures, air velocity, mass losses and times were measured with the appropriate instruments indicated before and total uncertainties for all these parameters were calculated using the method described by Akpinar and Bicer (2005). The sensitivity of temperature sensors was ±1.5 °C, reading errors for temperature measurements were assumed as ±1.5 °C and errors due to transfer of the data to computer by a RS232 connection were ±1.5 °C. The sensitivity of the power analyzer used in measuring microwave power was ±0.1 W and the reading error was also assumed to be ±0.1 W. The sensitivity of the digital balance used in measuring mass losses and moisture of the sample was ±0.01 g and reading errors were ±0.01 g. The uncertainty caused from vibration of the timer was assumed to be ±0.02 s, errors from the periodic measuring was assumed to be ±0.1 s and the errors recording temperature data were ±0.1 s. The uncertainties involved in the measurement of parameters are presented in Table 2.

**Table 2: Measurement uncertainties.**

| Parameter | unit | Value |
|---|---|---|
| Uncertainty in mass loss measurement | g | ±0.5 |
| Uncertainty in moisture quantity measurement | g | ±0.0141 |
| Uncertainty in the time measurement | s | ±0.141 |
| Uncertainty in microwave power measurement | W | ±0.10 |
| Uncertainty in temperature measurement | °C | ±2.12 |

## RESULTS AND DISCUSSION

### Energy Aspects

Figure 2 shows the effect of microwave power on the energy aspects of soybean drying. Results showed that the increase in the microwave drying power decreased the specific energy consumption and consequently increased drying efficiency and decreased energy loss. This was because of the dramatic reduction in the drying time with increase in microwave power (Doymaz, 2011; Wang and Sheng, 2006; Alibas, 2007). The values of specific energy consumption and drying efficiency of soybean seeds ranged from 9.11 to 4.93 MJ/kg water, and 33.70 to 66.0%, respectively (Figure 2). Specific energy loss varied from 8.89 to 5.04 MJ/kg water, which indicated that 67.4 to 86.1% of the energy given to the system was not used in drying the soybean samples (Figure 2). In the literature, although energy consumption for soybean seeds under fluidized bed and microwave-fluidized bed drying was studied by Darvishi *et al.* (2014b) and Khoshtaghaza *et al.* (2014), no mention was found about investigation of the energy consumption and drying efficiency for soybean seeds undergoing microwave treatment. Darvishi *et al.* (2014b) studied fluidized bed drying of soybean seeds and found that the specific energy consumption varied from 96.8 and 399.7 MJ/kg water for 140 ºC with 1.8 m/s and 80 ºC with 4.5 m/s air velocity, respectively. Khoshtaghaza *et al.* (2014) showed that the minimum energy required for microwave-fluidized bed drying of soybean kernels was 50.94 (MJ/kg water), which occurred at 500 W, 80 °C and 1.8 m/s, while the maximum energy requirement was 338.76 MJ/kg water observed at 200 W, 4.5 m/s and 100 °C. The values obtained in this present study, were lower than the values obtained by Darvishi *et al.* (2014b) and Khoshtaghaza *et al.* (2014), because of the lower drying times required under microwave treatment.

Figure 3 shows the average values (and percentage) of energy consumed in the sensible and evaporation (latent) periods of microwave drying of soybean seeds at different microwave powers. According to the results, approximately 11.27 to 14.45 kJ of the total energy input is consumed by increasing the product temperature (sensible heat).

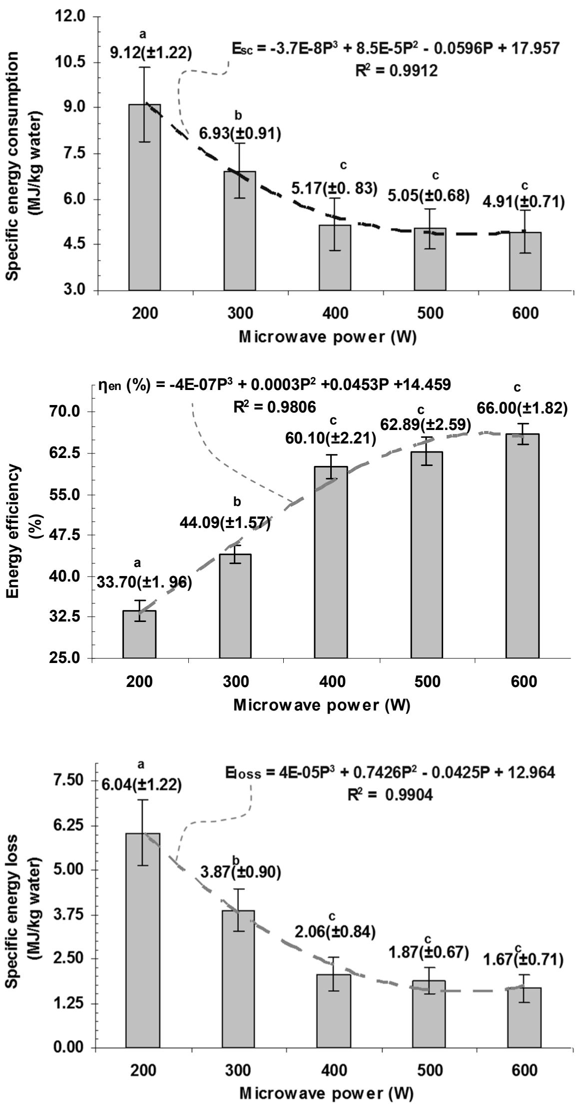

**Figure 2:** Energy aspects of soybean drying.

$^{a-c}$ Different superscripts in the same column indicate significant differences ($P < 0.05$)

$^{A}$ Values in parenthesis show the standard deviations

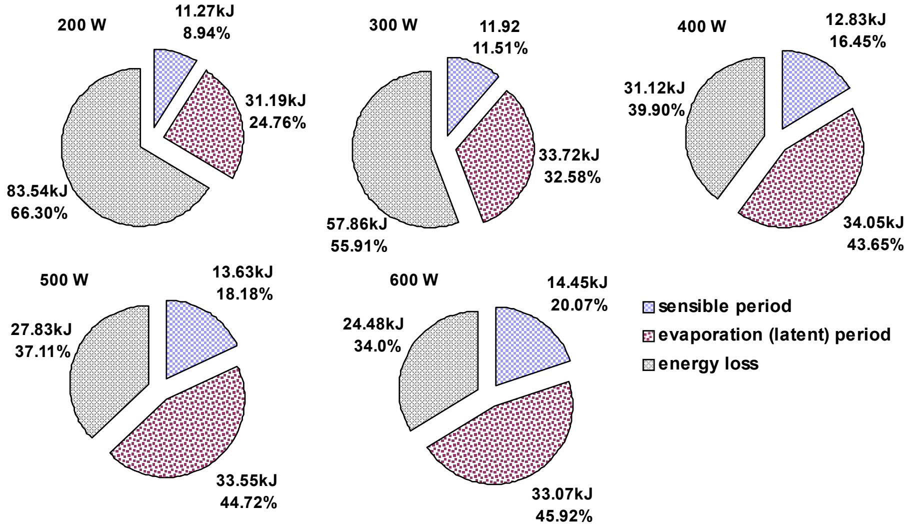

**Figure 3:** Energy consumed in the sensible and evaporation (latent) periods for microwave drying of soybean.

## Exergy Aspects

According to the results in Figure 4, the exergy efficiency increased with increasing microwave power. This can be explained by the fact that the surface moisture evaporates very quickly due to high heat and mass transfer coefficients at high microwave power, resulting in decreased drying time and consequently lower exergy consumption. The values of exergy efficiency for microwave drying of soybean studied were found to range between 23.38 – 48.30%, while the energy efficiency (Figure 4) was higher for the same condition ($P \leq 0.05$). These results were similar to the results of others (Darvishi *et al.*, 2104a, Akpinar *et al.*, 2006; Erbay and Icier, 2010).

Results showed that the specific exergy loss decreased with increasing microwave power (Figure 4; $P<0.05$). The values changed between 6.99 MJ/kg water and 2.54 MJ/kg water evaporation. These results are in contrast to the findings of Darvishi *et al.* (2014a) for microwave drying of white mulberry. These situations can be explained by the effect of drying time. An analysis of variance showed that the effect of drying time on exergy loss is more the effect of microwave power ($p \leq 0.05$). The drying time is longer under low microwave power levels, hence results in an increase in exergy entering to the drying chamber. For this reason, it was observed that, as the microwave power decreased, the energy losses increased, in other words microwave exergy efficiency values decreased.

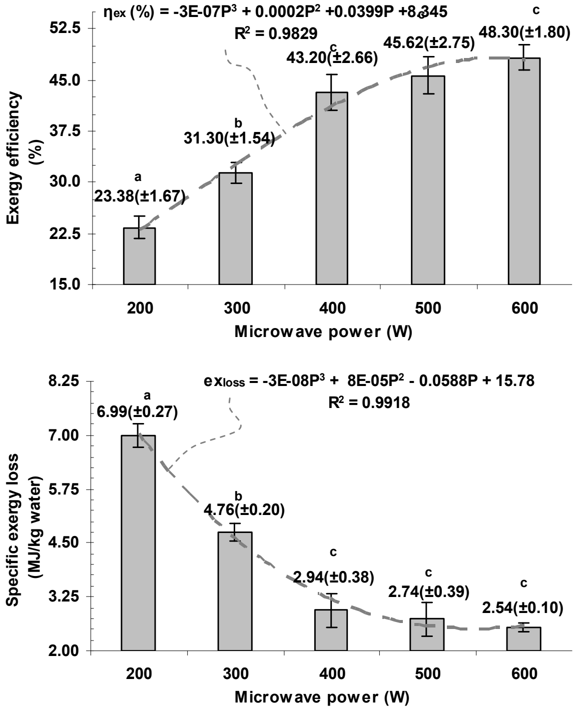

**Figure 4:** Exergy aspects of soybean drying.

[a–c] Different superscripts in the same column indicate significant differences ($P < 0.05$)

[A] Values in parenthesis show the standard deviations

The average values of specific improvement potential are presented in Figure 5. As was expected, when the microwave power was increased, the exergy loss decreased, and the improvement potential decreased from 5.35 to 1.31 MJ/kg water. The specific improvement potential obtained in the drying process using 600 W was 4.08-fold lower than 200 W microwave power levels.

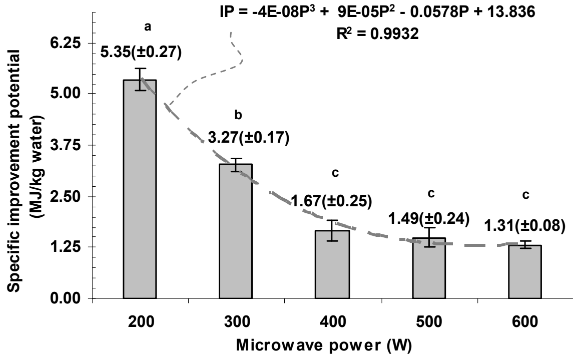

**Figure 5:** Average improvement potential at different microwave powers.

[a–c] Different superscripts in the same column indicate significant differences ($P < 0.05$)

[A] Values in parenthesis show the standard deviations

## Quality Aspects

The rehydration ratio of dried samples at 200–900 W varied in the range of 0.618 – 0.799 and increased with increasing microwave power (Table 3). The rehydration ratio at high microwave power improves rehydration due to the effect of temperature on cell wall and tissue (Singh *et al.* 2006; Doymaz and Ismail 2011). This can be explained by the high internal pressure produced by microwave heating, which can cause the structure of soybean seeds to expand. Also, Khoshtaghaza *et al.* (2014) reported that microwave heating had a significant effect on the rehydration ratio of soybeans (0.695 to 0.819), because the heat applied during drying increased both hydration of the starch and elasticity of the cell walls, thereby increasing the water-holding capacity.

Table 3 shows the colour parameters for dried soybean seeds as a function of microwave drying power. An increase in ΔE was observed with drying power. The total color change falls within the range reported for fluidized bed drying of soybean (ΔE = 19.29–23.41) (Darvishi, 2013) but higher than that reported for near-infrared-fluidized bed dried soybean seeds (ΔE = 2.9–4.2) (Dondee *et al.*, 2011). Microwave drying pushes liquid onto the surface and the liquid is usually converted into vapour. This process results in drying without causing surface overheating phenomena. Therefore, in terms of surface colour degradation, preservation of the product colour was good. It is estimated that the products are subjected to high temperature with increasing power levels during microwave drying. Therefore, the product colour is adversely affected in the drying processes at very high microwave powers (Ozkan *et al.*, 2007).

The Hue angle values also increased from about 88.07 to 91.73 during drying processes (Table 3). It suggested a reduction from a more green (when Hue > 90°) to an orange-red (when Hue < 90°) colour of the dried seeds (Waliszewski *et al.*, 1999). A larger value of the hue angle indicates a greater shift from red to yellow. Hawlader *et al.* (2006) stated that a decrease in hue angle values is an indication of more browning colour and a shifting away from yellowness, which is not the case in this study, where the values of hue angles increased with drying microwave powers, shifting towards yellow and red.

The variation of the bulk density at different microwave powers is illustrated in Figure 6. They ranged from 726.6 to 762.8 kg/m$^3$ for dried soybean seeds and decreased with increasing microwave power. Also, bulk density values for dried soybean were lower than the fresh soybean (783.4 kg/m$^3$). The shrinkage varied from 0.860 to 0.948 over the microwave power range (Table 3). Shrinkage decreased with increasing microwave power. During the drying process, water escapes the cell, causing a decrease in tension that the liquid exerts against the cell wall. This decrease in tension causes shrinkage of the materials (Hashemi *et al.*, 2009; Janjai *et al.*, 2010). Also, Mayor and Sereno (2004) reported that heating and loss of water cause stresses in the cellular structure of the food and this leads to changes in shape and a decrease in dimensions.

**Table 3: Different quality of soybean drying.**

| P (W) | ΔE (-) | h (degree) | Shrinkage | Rehydration ratio |
|---|---|---|---|---|
| 200 | 14.68 (±2.59[A])[a] | 88.07 (±5.11)[a] | 0.948 (±0.021)[a] | 0.618 (±0.019)[a] |
| 300 | 18.80 (±3.90)[ab] | 90.52 (±3.14)[a] | 0.897 (±0.024)[b] | 0.716(±0.017)[bc] |
| 400 | 18.13 (±3.54)[ab] | 91.51 (±7.41)[ab] | 0.885 (±0.034)[b] | 0.745 (±0.027)[c] |
| 500 | 19.61 (±7.46)[ab] | 91.73 (±9.47)[ab] | 0.860 (±0.011)[bc] | 0.703 (±0.039)[bc] |
| 600 | 19. 89 (±5.83)[ab] | 90.85 (±3.16)[ab] | 0.880 (±0.033)[bc] | 0.799(±0.029)[d] |

[a–b] Different superscripts in the same column indicate significant differences ($P < 0.05$)

[A] Values in parenthesis showed their standard deviations

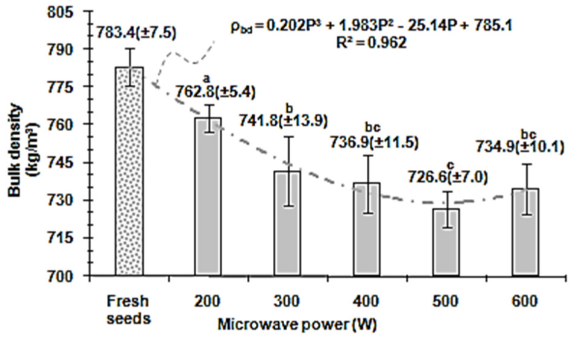

**Figure 6:** Comparison between bulk density of fresh and dried soybean at different microwave powers.
$^{a–c}$ Different superscripts in the same column indicate significant differences (P < 0.05)

## Drying Kinetics and Modeling

The changes in the moisture ratio of soybean with drying time are shown in Figure 7. It is clear that the moisture content decreases continuously with drying time. The moisture content of the samples was very high during the initial phase of the drying, which resulted in a higher absorption of microwave power and higher drying rates due to the higher moisture diffusion. As the drying progressed, the loss of moisture in the product caused a decrease in the absorption of microwave power and resulted in a fall in the drying rate. Higher drying rates were obtained at higher microwave output powers. In other words, as the microwave output power was increased, the drying time of samples was significantly decreased (P≤0.05). Examination of Figure 8 reveals that, in general, two distinct periods are identifiable, namely warming-up and falling rate periods. The initial short warming-up stage corresponds to sample heating, and consequently to non-isothermal drying conditions, this followed by a falling rate period. The presence of falling-rate drying behavior is indicative of a progressive increase in the internal resistance to both heat and mass transfer. This arises as a direct consequence of the absence of a complete surface of water. Rather, moisture movement from the interior to the surface must occur prior to surface evaporation. The drying time requirement at 200, 300, 400, 500, and 600 W was 10.5, 6.5, 3.25, 2.5 and 2 min respectively. By working at 600W instead of 200 W, the drying time was shortened by 81%. The drying time obtained in the present study was extremely low compared to the results obtained by Darvishi *et al*. (2014b) for fluidized bed drying of soybean (50-380 min), Dondee *et al*. (2011) for infrared-fluidized-bed drying (≥120 min), Darvishi *et al*. (2014b) for microwave-fluidized bed drying (3.3-38.5 min), Rafiee *et al*. (2009) for convective drying of soybean (70-210 min), Gowen *et al*. (2008) for microwave–hot-air drying (20-120 min), Sangkram and Noomhrom, (2002) for hot air drying (120-450 min).

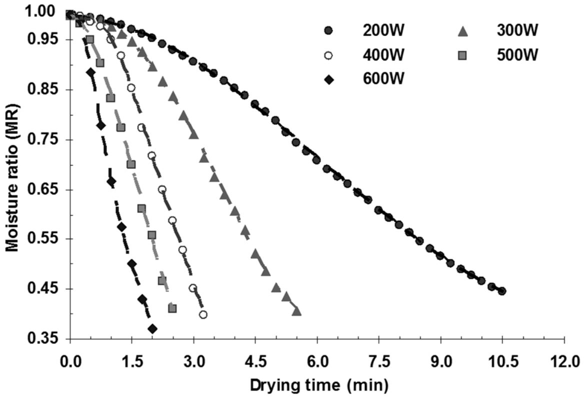

**Figure 7:** Drying curves of soybean at various microwave powers.

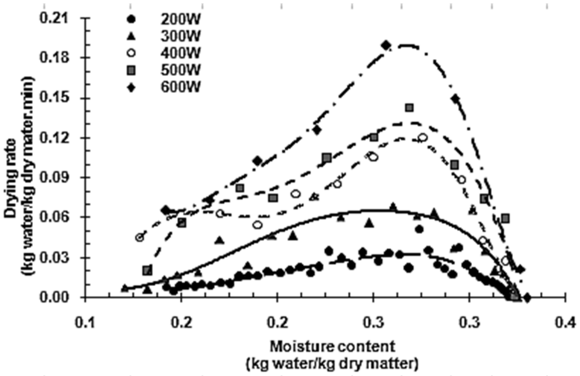

**Figure 8:** Variation of drying rates with moisture content soybean seeds.

The statistical results from models are summarised in Table 4. The statistical parameter estimations showed that $R^2$, $\chi^2$ and RMSE values ranged from 0.8295 to 0.9997, 0.00004 to 0.13272, and 0.00060 to 0.34078, respectively. The level of $\chi^2$ as well as $R^2$ for the Midilli and Page models were always very close to each other. Although the Midilli model showed the best fit among the selected models, the Page model was selected as the appropriate model for this research because it is simple with two parameters while the Midilli model has four parameters.

It was determined that the value of the drying constant k increased with the increase in microwave power. This data points out that, with an increase in the microwave output power, the drying curve becomes steeper, indicating faster drying of the product. The relationship between the constants of the Page model and the air temperature can be represented as:

$$k = 0.0028 \exp(0.0081P) \qquad R^2 = 0.991 \qquad (30)$$

$$n = 0.0782 + 0.011P - 1.47 \times 10^{-5} P^2 \quad R^2 = 0.904 \quad (31)$$

Figure 9 compares the experimental data with the predicted ones using the Page model for soybean samples. The prediction using the Page model showed MR values distributed along a straight line, which proved the suitability of this model in describing the drying characteristics of soybean samples.

**Table 4: Statistical analysis of the models fitted to the drying data for microwave drying soybean seeds.**

| Model | P (W) | Coefficients and constants | $R^2$ | $\chi^2$ | RMSE |
|---|---|---|---|---|---|
| Newton | 200 | k = 0.0664 | 0.9176 | 0.00328 | 0.05656 |
| | 300 | k = 0.1301 | 0.8583 | 0.00710 | 0.08249 |
| | 400 | k = 0.2147 | 0.8295 | 0.00892 | 0.09101 |
| | 500 | k = 0.2966 | 0.922 | 0.00467 | 0.06515 |
| | 600 | k = 0.4596 | 0.9601 | 0.00313 | 0.05277 |
| Henderson and Pabis | 200 | a = 1.1224, k = 0.0827 | 0.9684 | 0.00168 | 0.03997 |
| | 300 | a = 1.1697, k = 0.1719 | 0.9336 | 0.00441 | 0.06358 |
| | 400 | a = 1.1775, k = 0.2873 | 0.9100 | 0.00658 | 0.07507 |
| | 500 | a = 1.1264, k = 0.3647 | 0.9485 | 0.00351 | 0.05362 |
| | 600 | a = 1.1036, k = 0.5291 | 0.9842 | 0.00209 | 0.04031 |
| Page | 200 | k = 0.0154, n = 1.704 | 0.9977 | 0.00005 | 0.00690 |
| | 300 | k = 0.0256, n = 2.116 | 0.9980 | 0.00009 | 0.00913 |
| | 400 | k = 0.0601, n = 2.260 | 0.9974 | 0.00066 | 0.02386 |
| | 500 | k = 0.1762, n = 1.781 | 0.9992 | 0.00004 | 0.00572 |
| | 600 | k = 0.3791, n = 1.462 | 0.9940 | 0.00038 | 0.01726 |
| Wang and Singh | 200 | b = -0.0301, a = -0.0016 | 0.9990 | 0.00270 | 0.05067 |
| | 300 | b = -0.0291, a = -0.0129 | 0.9889 | 0.00241 | 0.04701 |
| | 400 | b = -0.0239, a = -0.0468 | 0.9990 | 0.00164 | 0.03752 |
| | 500 | b = -0.1168, a = -0.0422 | 0.9940 | 0.00128 | 0.03232 |
| | 600 | b = -0.2959, a = $-1.012\times10^{-9}$ | 0.9819 | 0.00246 | 0.04370 |
| Logarithmic | 200 | a = 1.505, b = -0.409, k = 0.0521 | 0.9777 | 0.00108 | 0.03169 |
| | 300 | a = 1.539, b = -0.395, k = 0.1114 | 0.9522 | 0.13272 | 0.34078 |
| | 400 | a = 1.392, b = -0.240, k = 0.2120 | 0.9231 | 0.00751 | 0.07682 |
| | 500 | a = 1.291, b = -0.183, k = 0.2861 | 0.9579 | 0.00304 | 0.04702 |
| | 600 | a = 1.314, b = -0.234, k = 0.3846 | 0.9881 | 0.00159 | 0.03252 |
| Midilli | 200 | a= 0.994, b= 0.030, k= 0.019, n= 1.958 | 0.9990 | 0.00026 | 0.00560 |
| | 300 | a= 0.993, b= 0.025, k= 0.037, n= 2.069 | 0.9991 | 0.00019 | 0.01261 |
| | 400 | a= 0.995, b= 0.039, k= 0.092, n= 2.024 | 0.9995 | 0.00007 | 0.00714 |
| | 500 | a= 1.000, b= 0.002, k= 0.178, n= 1.781 | 0.9997 | 0.00006 | 0.00060 |
| | 600 | a= 1.009, b= 0.095, k= 0.556, n= 1.605 | 0.9993 | 0.00011 | 0.00807 |

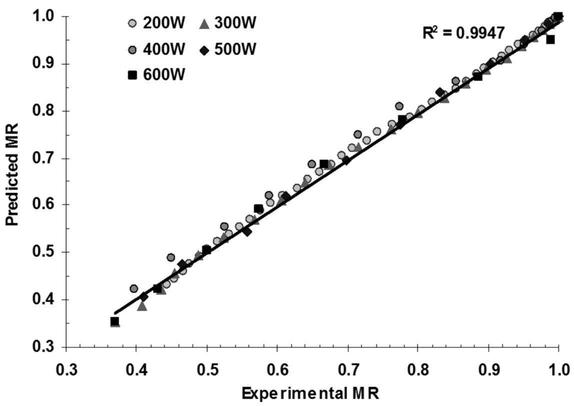

**Figure 9:** Comparison between experimental and predicted moisture ratios using Page's model.

## Moisture Diffusivity and Mass Transfer Coefficient

According to the results in Figure 10, the microwave power level had a significant effect on the moisture diffusivity of the soybean seeds, as expected ($P<0.05$). Effective diffusivity varied from $1.99\times10^{-9}$ to $12.25\times10^{-9}$ $m^2/s$ and increased greatly with increasing microwave power. This might be explained by the increased heating energy, which would increase the activity of the water molecules, leading to higher moisture diffusivity when samples were dried at higher microwave power. These values fell within the normally expected range of $D_{em}$ ($10^{-11}$ to $10^{-9}$ $m^2/s$) for food materials (Arumuganathan *et al.*, 2009). The resultant values of $D_{em}$ are comparable to $6.25\times10^{-10}$ to $42.14\times10^{-10}$ $m^2/s$ mentioned for microwave-fluidized bed drying of soybean seeds (Khoshtaghaza *et al.*, 20114); $1.22\times10^{-10}$ to $2.86\times10^{-10}$ $m^2/s$ for wheat (Mohapatra and Rao, 2005); $4.595\times10^{-11}$ to $3.325\times10^{-10}$ $m^2/s$ for fluidized bed drying of soybean, (Darvishi *et al.*, 2014b); $1.39\times10^{-10}$ to $5.72\times10^{-10}$ $m^2/s$ for hot air-infrared drying of green peas (Eshtiagh and Zare, 2015); and $1.79\times10^{-10}$ to $5.87\times10^{-10}$ $m^2/s$ for microwave drying of millet (Radhika *et al.*, 2013). The values obtained in this study are higher than those found by Darvishi *et al.* (2014b) and Khoshtaghaza *et al.* (20114) for the fluidized bed and microwave-fluidized bed drying of soybean, respectively. This is due to the fact that drying by microwave power, which leads to higher temperatures, implied a larger driving force for heat transfer, as compared with fluidized bed or microwave-fluidized bed drying. In other words, in microwave drying, the volumetric heat generation in the wet sample due to the directly transmitted and absorbed energy by the water molecules results in higher interior temperatures and increase the activity of water molecules, thus reaching the boiling point of water substantially faster than would be possible in convective drying. The rate of $D_{liquid}/D_{vapor}$ was given as 1/10,000 by Reid *et al.* (1987). This value is important for the use of microwave dryers in the food industry and explains the higher total diffusivity obtained in this study at lower moisture content compared to the results obtained in fluidized bed drying. In the case of fluidized bed drying, the moisture is in liquid phase form in capillary vessels of seeds. All capillary vessels in seeds have different widths. The vapor occurring on the water surface in these capillary vessels is transported from the water surface to the fruit surface during drying. The vapor transport velocity in a narrow capillary vessel is higher than in a wide capillary vessel. Therefore, in the case of fluidized bed drying, water crosses between two different width capillary vessels. But, in the microwave drying, the amount of water crossing between vessels is lower than in fluidized bed drying. Since a material is heated intensely, the temperature gradient in the material is formed within a short period and vapor transportation in all different width vessels is higher than water crossing between capillary vessels (Caglar *et al.*, 2009).

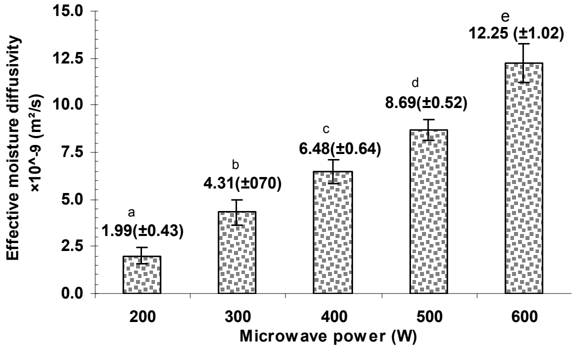

**Figure 10:** Variation of effective diffusivity for soybean with microwave power.
$^{a–e}$ Different superscripts in the same column indicate significant differences ($P < 0.05$)

Figure 11 shows the changes of the mass transfer coefficient with microwave power. The values of the mass transfer coefficient vary from $2.71\times10^{-6}$ m/s at 200 W to $19.98\times10^{-6}$ m/s at 600 W. It is apparent that $h_m$ increased with the increase in microwave power. When samples were dried at higher power, increased heating energy would increase the activity of water molecules, resulting in a higher mass transfer rate (Thuwapanichayanan *et al.*, 2011; Rhim and Lee, 2011). Additionally, these values are comparable to $5.13\times10^{-7}$ to $27.8\times10^{-6}$ m/s for drying of pumpkin (Raquel *et al.*, 2012); $16.1\text{x}10^{-9}$ m/s for drying of okra (Dincer and Hussain, 2002), $20.9\times10^{-7}$ to $32.8\times10^{-6}$ m/s for drying potato slabs (McMinn *et al.*, 2003), and $9.2\times10^{-8}$ to $26.4\times10^{-8}$ m/s for drying of banana (Queiroz and Nebra, 2001).

## Activation Energy

The functions expressing the variations of $D_m$ and $h_m$ versus the mass of sample/power [$m_0/P$] are presented in Figures 12-13. The activation energy values were found to be 4.98 W/g for the diffusion model and 5.33 W/g for the mass transfer model. These results indicate that the activation energy for the mass transfer model is higher than that for the diffusion model. These values are comparable to 13.6 W/g for pandanus leaves (Rayaguru and Routray, 2011), 14.19 W/g for pepper (Darvishi *et al.*, 2014c), 5.54 W/g for okra (Dadali *et al.*, 2007), 12.284 W/g for mint leaves (Ozbek and Dadali, 2007), and 3.986 W/g for white mulberry (Darvishi *et al.*, 2014a). The lower activation energy translates to higher moisture diffusivity or mass transfer coefficient in the drying process (Sharma and Prasad, 2004).

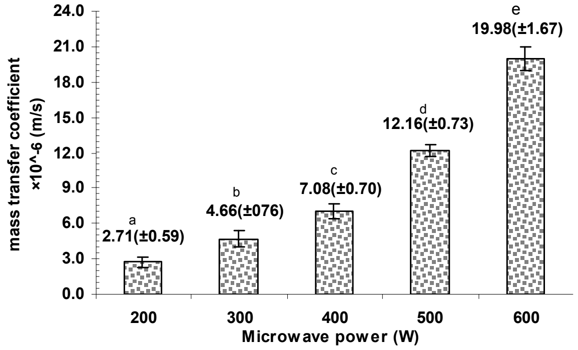

**Figure 11:** Effect of microwave power on mass transfer coefficient of soybean seeds.
$^{a–e}$ Different superscripts in the same column indicate significant differences (P < 0.05)

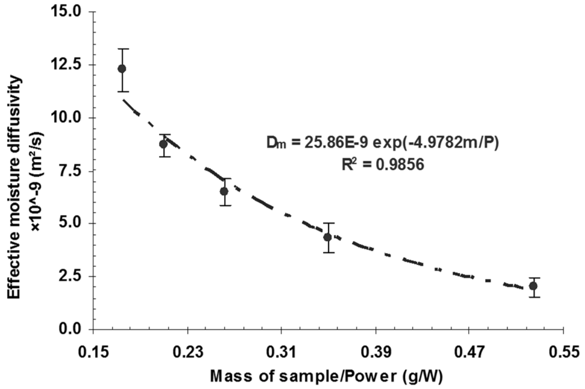

**Figure 12:** Fitting of the experimental points to the Arrhenius relationship for the diffusion model.

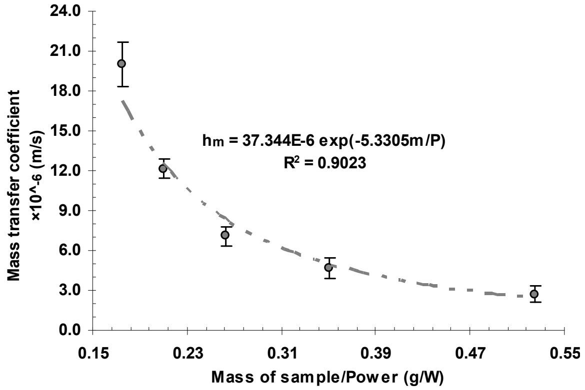

**Figure 13:** Fitting of the experimental points to the Arrhenius relationship for the mass transfer model.

## CONCLUSIONS

Moisture content of soybean kernel at harvest time is too high for storage, and needs to be reduced. In this research, energy and exergy analyses of drying characteristics, quality and mass transfer parameters for microwave drying of soybean seeds were studied and the process was modeled. Results showed that values of the energy efficiency (33.70 to 66.0%) were higher than exergy efficiency (23.38 – 48.30%). The values of specific energy consumption and improvement potential varied from 4.93 to 9.11 MJ/kg water, and 1.31 to 5.35 MJ/kg water, respectively. Increasing the microwave power decreases both the shrinkage and bulk density of soybean. Colour analysis showed that the values of the parameters ΔE and h increased with microwave power, shifting it towards yellow and red. The highest rehydration capacity (0.799) was recorded for the samples dried at 600 W and the lowest (0.618) at 200 W. The moisture diffusivity and mass transfer coefficient varied from $1.99\times10^{-9}$ to $12.25\times10^{-9}$ $m^2/s$ and $2.71\times10^{-6}$ to $19.98\times10^{-6}$ m/s, respectively. The activation energy was found to be 4.98 W/g and 5.33 W/g for the diffusion and mass transfer models, respectively. It is expected that this research will help growers reduce the cost of drying and obtain better quality dried soybeans. They are also usable in dryer design for scale up work.

## NOMENCLATURE

| | |
|---|---|
| a, b, n | experimental constants |
| $A_p$ | sample surface area, ($m^2$) |
| $C_p$ | specific heat capacity, (J/kg.K) |
| $D_0$ | pre-exponential factor of the Arrhenius equation, ($m^2/s$) |
| $D_{em}$ | moisture diffusivity, ($m^2/s$) |
| Dr | drying rate, (kg water/kg dry matter, (s) |
| $E_{ab}$ | energy absorbed, (J) |
| $E_{ad}$ | activation energy for the diffusion model, (W/g) |
| $E_{am}$ | activation energy for the mass transfer model, (W/g) |
| $E_{loss}$ | specific energy loss, (J/kg water) |
| $E_{ref}$ | energy reflected, (J) |
| $E_{tran}$ | energy transmition, (J) |
| $E_{sc}$ | specific energy consumption, (J/kg water) |
| ex | specific exergy, (J/kg) |
| $ex_{evap}$ | rate of exergy evaporation, (J/s) |
| $EX_{loss}$ | specific exergy loss, (J/kg) |
| $EX_{ref}$ | exergy reflected, (J) |

| | |
|---|---|
| $EX_{tran}$ | exergy transmission, (J) |
| $F_0$ | Fourier number, (dimensionless) |
| h | hue angle, (degree) |
| $h_0$ | pre-exponential factor of the Arrhenius equation, (m/s) |
| $h_m$ | mass transfer coefficient, (m/s) |
| IP | improvement potential, (J) |
| k | drying rate constant, (1/s) |
| m | mass of sample, (kg) |
| $m_t$ | mass of sample at any time, (kg) |
| $m_0$ | initial mass of sample, (kg) |
| $m_d$ | mass of dry product, (kg) |
| $m_w$ | mass of evaporated water, (kg) |
| $\dot{m}_w$ | rate of evaporated water, (kg/s) |
| $M_0$ | initial moisture content, (kg water/kg dry matter) |
| $M_e$ | equilibrium moisture content, (kg water/kg dry matter) |
| $M_t$ | moisture content at any time, (kg water/kg dry matter) |
| MR | moisture ratio, (dimensionless) |
| $MR_{exp,i}$ | $i^{th}$ experimental moisture ratio |
| $MR_{pre,i}$ | $i^{th}$ predicted moisture ratio |
| N | number of observations |
| P | microwave power, (W) |
| $P_{in}$ | microwave power emitted by the magnetron, (W) |
| r | radius of sample, (m) |
| $R^2$ | coefficient of determination |
| RMSE | root mean square error |
| Rr | Rehydration ratio |
| Sh | shrinkage, (-) |
| t | time, (s) |
| T | temperature, (K) |
| $T_o$ | ambient temperature, (K) |
| $T_p$ | temperature of product, (K) |
| $V_c$ | volume of the cylinder, ($m^3$) |
| $V_d$ | volume of the dry sample, ($m^3$) |
| $V_f$ | volume of the fresh sample, ($m^3$) |
| $V_p$ | sample volume, ($m^3$) |
| z | number of constants in the drying model |

### *Greek Symbols*

| | |
|---|---|
| $\eta_{en}$ | energy efficiency, (%) |
| $\eta_{ex}$ | exergy efficiency, (%) |
| $\lambda_{fw}$ | latent heat of free water, (J/kg) |
| $\lambda_{wp}$ | latent heat of product, (J/kg) |
| $\rho_b$ | bulk density, (kg/$m^3$) |
| $\Delta E$ | total colour change |

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