

Modelling the Drying Kinetics of Canola in Fluidised Bed Dryer

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Abstract

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Canola, one of the new oil seeds in Iran, is investigated for drying in Batch fluidised beds. Experiments were conducted to assess the kinetics of drying in the temperature range of 30–100°C. The drying rate was found to increase significantly with increasing temperature. The drying rate was compared with various exponential time decay models and the model parameters were evaluated. The approximate diffusion and logarithmic models were found to match the experimental data very closely with the maximum Root Mean Square Error (RMSE) less than 0.02. Considering fewer differences in the model evaluation factors and friendly use, logarithmic model was recommended for modelling canola drying. The experimental data were also modelled using Fick's diffusion equation, the effective diffusivity coefficients having been found to be from $3.76 \times 10^{-11} \text{ m}^2/\text{s}$ to $8.46 \times 10^{-11} \text{ m}^2/\text{s}$ in the range of experimental data covered in the present study. For the process, the activation energy was calculated to be 11.03 kJ/mol assuming an Arrhenius type temperature reliance.

Keywords: canola; fluidised bed; drying kinetics; food grain drying; activation energy

Canola oil is one of the good vegetable oils that have been developed rapidly in many parts of world such as Iran. The plants are generally harvested before fruits are fully ripe to reduce shattering. Conventionally, canola is harvested when seeds have 12–14% (d.b.) moisture content. The north provinces of Iran have high relative humidity and rainfall in the harvesting season, thus the moisture content of canola can reach more than 16% (d.b.) during harvesting. For safe storage, the moisture content of the harvested canola oil seeds needs to be reduced to less than 8% (d.b.) (WARD *et al.* 1985). Batch, continuous flow, and bin drying are the methods which have been employed for canola drying (MUJUMDAR 1995). However, they are slow and with high energy consumption, therefore it is necessary to study some other methods to improve the drying process of canola.

Due to a better heat and mass transfer, shorter drying time, better quality of the products obtained,

and shorter reconstitution time (BOBIC *et al.* 2001; BAUMAN *et al.* 2005), Fluidised Bed Drying (FBD) is commonly used for drying particulate materials like grain and fruits. In FBD, the conditions are favourable for a rapid heat and mass transfer. Due to the rapid drying, FBD has been considered as an economical drying method in comparison with other drying techniques. FBD has been also recognised as a gentle, uniform drying procedure, resulting in a very low residual moisture content, with a high degree of efficiency (BORGOLTE & SIMON 1981). This technique is very convenient for heat sensitive food materials as it prevents them from overheating (GIBERT *et al.* 1980; GINER & CALVELO 1987). A large number of FBD experiments have been reported during the past few years to investigate its results obtained with different products (KALWAR *et al.* 1991; DIAMATTIA *et al.* 1996; SENADEERA *et al.* 2003; BAUMAN *et al.* 2005; SRINIVASAKANNAN 2008).

The knowledge of drying kinetics is important in the design, simulation, and optimisation of drying processes. Drying curves are usually modelled by defining the drying rate constants based on first order kinetics. Numerous mathematical models have been developed to calculate the time of drying under the given operating conditions (MUJUMDAR 1995; TURNER & MUJUMDAR 1996). This range of analytical models solved with a variety of simplifying assumption leads to purely empirical models often built by regression on experimental data. An example is the exponential equation to model time-temperature variation of the reduced moisture content for various seeds and vegetables dried in the pulsed FB dryer (GAWRZYNSKI & GLASER 1996).

A series of empirical models based on exponential time decay have been developed to represent the drying kinetics of agricultural materials in FB dryer (SENADEERA *et al.* 2003; BAUMAN *et al.* 2005; SRINIVASAKANNAN 2008). The Page model was found to match the experimental data very closely for mustard drying (SRINIVASAKANNAN 2008). It was found that the drying takes place only in the falling rate period for beans, potato, and peas. Both the simple (exponential) and Page models could be used to describe the drying behaviour, but the Page model was shown to describe the drying behaviour more accurately (SENADEERA *et al.* 2003). Therefore, the objectives of this study are:

- to study the effect of temperature on air drying kinetics of canola seed samples in a fluidised bed dryer,
- to fit the drying curves with six empirical models,
- to calculate the diffusivity coefficients of the samples and the activation energy.

MATERIALS AND METHODS

Experimental procedure. Canola seeds used in the experiments were collected randomly from an Agricultural Engineering Research Institute (AERI) farm in Karaj and transferred to the laboratory in PE plastic bags in order to conduct the drying experiments. Table 1 shows the physical characteristics of Canola seed as well as the experimental conditions covered in the present study.

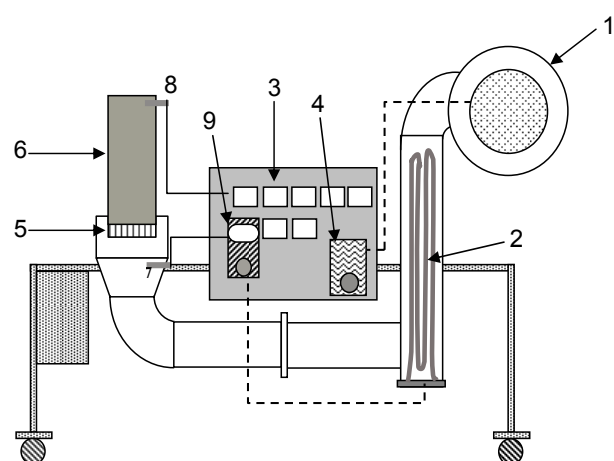
The drying experiments were conducted using a fluidisation column with the internal diameter of 0.2 m and a height of 0.3 m and were replicated three times. The air distributor was 1.5×10^{-3} m

Table 1. Characteristics of the seed and the range of experimental parameters

Seeds parameter	Canola seed (<i>Brassica napus</i> L.)
Shape of seeds	spherical
Size, $dp \times 10^{-3}$ (m)	1.90
Particle density (kg/m^3)	670
Initial moisture content of seeds* (% d.b.)	20
Temperature of fluidizing air ($^{\circ}\text{C}$)	30, 40, 50, 60, 70, 80, 90, 100
Fluidising air velocity (m/s)	1.0
Solid hold up (kg)	2.2

*for more uniformity of moisture content, seeds were conditioned

thick with 5×10^{-3} m perforations having 40% free area. A fine wire mesh was attached over the distributor plate to arrest the flow of solids from the fluidised bed into the air chamber. Air blower with the volumetric discharge capacity of $500 \text{ m}^3/\text{h}$ was used. The outlet air from the dryer column was metered using a calibrated anemometer (Lutron AM-4205, Taipei, Taiwan) after the fluidisation column. The electrical heater consisted of three 1 kW rating heating elements. A temperature controller, provided to the air chamber, facilitated the control of the air temperature within $\pm 1^{\circ}\text{C}$ of the temperature set (Figure 1).



(1) blower, (2) electrical heaters, (3) thermometers, (4) blower regulator, (5) air distributor, (6) dryer column, (7) inlet thermocouple, (8) out let thermocouple, (9) inlet air thermostat

Figure 1. Schematic of fluidized bed dryer

Air at the desired temperature and flow rate was allowed to flow through the fluidisation column. 2.2 kg canola with 20% (d.b.) of the initial moisture content was introduced into the column after ensuring steady temperature and air flow rate. The moisture loss was recorded in 30 min intervals with a digital balance of 1 g accuracy (Tozin Electric, Teheran, Iran). The pressure drop was measured by differential pressure meter (Testo 506 – Testo, Lenzkirch, Germany) blow of the drying column. The drying was continued until each sample reached the constant weight. The final moisture content of each sample was determined with the help of an atmospheric drying oven using AOCS (2003) method.

Analysis of process and modelling. The moisture ratio of the samples during drying was expressed by the following equation:

$$MR = \frac{M - M_e}{M_i - M_e} \quad (1)$$

During drying, the samples in the FBD were not continuously exposed to uniform relative humidity and temperature. Therefore, the moisture ratio was simplified according to PALA *et al.* (1996), DOYMAZ (2004a), and GOYAL *et al.* (2007), and expressed as:

$$MR = \frac{M}{M_i} \quad (2)$$

To select a suitable model for describing the drying process of canola seed, drying curves were fitted with six thin-layer drying equations (Table 2). Non-linear regression analysis was performed using Statistica 6.0 software package. The coefficient of determination (R^2) was one of the main criteria for selecting the best equation. In addition to the

Table 2. List of various simple models tested with the drying data (AKPINAR & BICER 2006; SRINIVASAKANNAN 2008)

Name of model	Model equation
Newton (NM)	$MR = \exp(-kt)$
Page (PM)	$MR = \exp(-ktn)$
Henderson and Pabis (HPM)	$MR = a \exp(-kt)$
Two term exponential (TEM)	$MR = a \exp(-kt) + (1 - a) \exp(-kat)$
Approximate Diffusion (ADM)	$MR = a \exp(-kt) + (1 - a) \exp(-kbt)$
Logarithmic (LM)	$MR = a \exp(-kt) + b$

coefficient of determination, the goodness of fit was determined by other statistical parameters such as reduced mean square of the deviation (X^2) and root mean square error (RMSE). For goodness fitting, R^2 value should be higher and X^2 and RMSE values should be lower (SARSAVADIA *et al.* 1999; TOGRUL & PEHLIVAN 2002; DEMIR *et al.* 2004; ERENTURK *et al.* 2004; GOYAL *et al.* 2006; AKPINAR & BICER 2006; SRINIVASAKANNAN 2008). These parameters are calculated as follows:

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^n (MR_{exp,i} - MR_{pre,i})^2 \right]^{1/2} \quad (3)$$

$$X^2 = \frac{\sum_{i=1}^n (MR_{exp,i} - MR_{pre,i})^2}{N - n} \quad (4)$$

Moisture diffusivity. Fick's diffusion equation for the particles spherical in shape was used for the calculation of effective moisture diffusivity (MUJUMDAR 2000; SENADEERA *et al.* 2003). Since the Canola seeds have spherical geometry, the equation is expressed as:

$$MR = \frac{6}{\pi^2} \exp \left[-\frac{\pi^2 D_{eff} t}{r^2} \right] \quad (5)$$

The effective diffusivity was calculated using the slopes method. The diffusion coefficient was typically calculated by plotting the experimental drying data in terms of $\ln(MR)$ versus the drying time (MASKAN *et al.* 2002; GOYAL *et al.* 2006; SRINIVASAKANNAN 2008). Effective diffusivity can be expressed by using an Arrhenius type equation (FALADE & ABBO 2007) as follows:

$$D_{eff} = D_o \exp \left(\frac{E_a}{RT} \right) \quad (6)$$

The E_a and D_o coefficients can be subsequently related to the drying air temperature by applying non-linear regression analysis.

RESULTS AND DISCUSSION

Fluidisation

A good fluidisation behaviour in terms of perfect mixing of the bed material was clearly observed. This was substantiated with a low fluctuation in the bed pressure drop, which was an indication for smooth fluidisation without slugs formation. As Figure 2 shows, pressure drop below of the seed

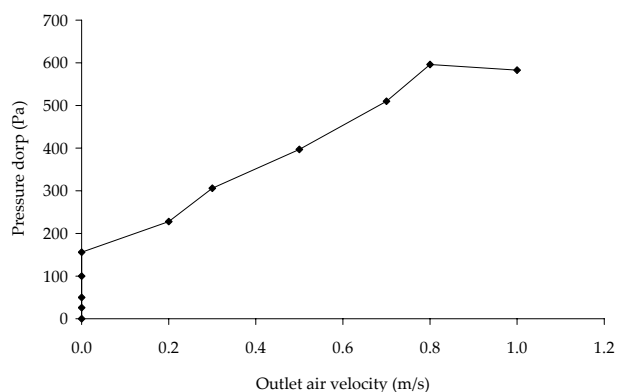
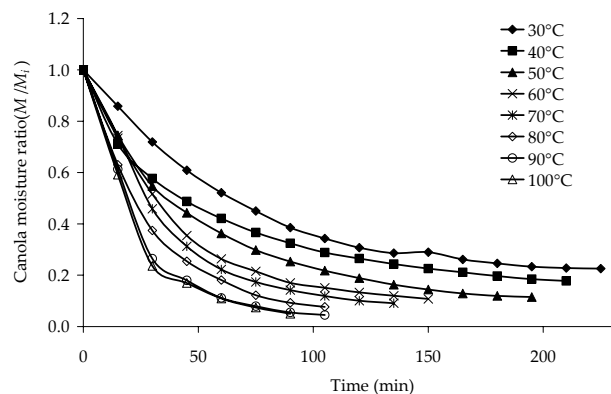


Figure 2. Pressure drop changes vs. air flow speeds

bulk has increasing trend by rise up the air flow rate until moment of fluidising. It decreases from 596 Pa to 583 Pa after the threshold of fluidising and outlet air velocity of 1 m/s (BAUMAN *et al.* 2005; SRINIVASAKANNAN 2008).

Drying kinetics and modelling

The experimental data generated in the present study are depicted in Figure 3 as plots of canola moisture ratio (M/M_i) vs time. In general, it can be observed in Figure 3 that the duration of the constant drying rate period is insignificant as compared to the total drying time. The rate of drying was high at the early stage of drying and became low as the moisture content decreased. An increase in temperature increased the drying rate and that can be attributed to the higher bed temperature of the particles in the bed, which increases the intra particle moisture diffusion leading to a higher drying rate. The increased transport properties of the fluids with the increase in temperature has been well

Figure 3. Effect of temperature on drying process (V_{out} : 1.0 m/s; W : 2.2 kg).

known and the experimental data are in concurrence with the basic concepts of the mass transfer. A higher bed temperature increases the moisture diffusion rate, resulting in an increased drying rate. All the observations are in qualitative agreement with most of the earlier observations (SYAHRUL *et al.* 2002; KUDRAS & EFREMOV 2003; TOPUZ *et al.* 2004).

The experimental drying data were converted to the dimensionless moisture ratio (M/M_i) for the sake of comparison with various models. The simple exponential time decay models listed in Table 2, were compared with the experimental data.

Table 3 compares the model parameters along with the R^2 , X^2 , and RMSE values for all models. The RMSE values were found to be above 0.02 for all the models except the Approximation of Diffusion model (ADM) and the Logarithmic model (LM). It can be seen from the table that ADM matches the experimental data very closely, with the RMSE error equal 0.0126.

The standard deviation between the experimental data and the model prediction was smaller than 0.0004

Table 3. Evaluated model parameters at operating conditions

Models	Evaluated model parameters and coefficients						
	b	k	n	A	RMSE	X^2	R^2
NM	0.792	0.0116	0.1041	–	–	0.017500	–
PM	0.944	0.0035	0.0546	–	0.520637	0.131005	–
HPM	0.825	0.0107	0.0965	0.864356	–	0.014294	–
TEM	0.865	0.0082	0.0845	0.272140	–	0.047495	–
ADM	0.997	0.0002	0.0126	0.885148	–	0.030828	–0.086850
LM	0.995	0.0003	0.0165	0.835414	–	0.035451	0.179319

NM – Newton model; PM – Page model; HPM – Henderson and Pabis model; TEM – Two term exponential model; ADM – Approximation of Diffusion model; LM – Logarithmic model

Table 4. Specified coefficients at experimental temperatures for the logarithmic model

Temperature (°C)	R^2	a	K	b
30	0.999	0.822350	0.015413	0.192238
40	0.996	0.775869	0.021012	0.189018
50	0.999	0.877656	0.021233	0.110473
60	0.999	0.923380	0.026423	0.089113
70	0.997	0.957696	0.028384	0.064102
80	0.999	0.950969	0.034426	0.051497
90	0.996	0.986383	0.041044	0.027275
100	0.995	0.982796	0.043	0.029348

for ADM and LM. The comparison between ADM and LM showed that LM had a simpler form than ADM due to less difference between them. It follows that LM can be introduced as a suitable model for describing the drying kinetic of canola in FB.

Considering less difference between ADM and LM models evaluation factors and friendly use, LM has been recommended for modelling canola drying. Table 4 shows the specified coefficients of LM at different temperatures. Figure 4 shows the proximity of the logarithmic model with the experimental data. The model parameters estimated the drying time as well as the designing and scaling up of the drying process.

Calculation of effective moisture diffusivity

The effective diffusivity was calculated using the slopes method (MASKAN *et al.* 2002; DOYMAZ 2004b). Table 5 shows the effective moisture diffusivity for Table 5. Effective moisture diffusivity for drying of canola seeds

Temperature (°C)	D_{eff} (m ² /s)	R^2
30	3.76×10^{-11}	0.987
40	4.06×10^{-11}	0.978
50	4.70×10^{-11}	0.963
60	4.91×10^{-11}	0.999
70	5.64×10^{-11}	0.986
80	6.58×10^{-11}	0.982
90	7.52×10^{-11}	0.988
100	8.46×10^{-11}	0.994

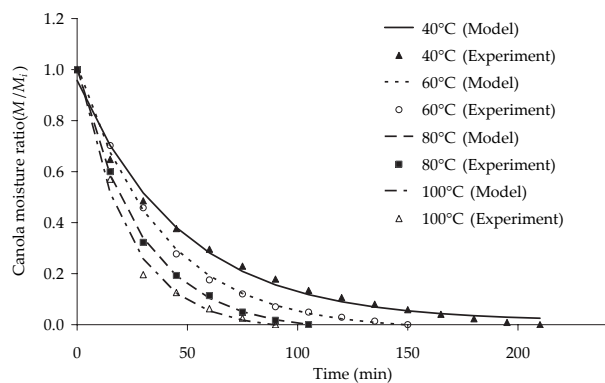


Figure 4. Comparison of Logarithmic model prediction with the experimental data (40, 60, 80 and 100°C).

canola seeds drying. The values of the moisture diffusivity were found to vary in the range of 3.76×10^{-11} m²/s to 8.46×10^{-11} m²/s and were close to 1.69×10^{-11} m²/s to 3.26×10^{-11} m²/s given by SRINIVASAKANNAN (2008) for Mustard seeds. The effective diffusivity increases with the increase in drying temperatures. These values are within the range of 10^{-8} – 10^{-12} m²/s for the drying of food materials (UCKAN & ULKU 1986; ZOGZAS *et al.* 1994; MASKAN *et al.* 2002; AKPINAR *et al.* 2003; SENADEERA *et al.* 2003). In the present study, the estimated effective diffusion coefficient is compared with those for other grains reported in the literature and found to be within the same order of magnitude.

Plots of $\ln D_{\text{eff}}$ versus reciprocal of absolute temperature ($1/T$) indicated a good fit with a high coefficient of determination ($r^2 = 0.977$). The calculated activation energy showed that canola seeds required low activation energy for mass diffusion during FBD (11.03 kJ/mol). That was near to the activation energy for the drying of breadfruits seeds in the range of 40–70°C (SHITTU & RAJI 2008).

CONCLUSION

The drying rate in FBD was found to be high at increased temperatures. In addition, the drying time decreased with increasing temperature.

The kinetics of drying was tested with various simple exponential decay models, Approximate Diffusion and logarithmic models having been found to match with the experimental data very closely.

The experimental data were modelled using fundamental Fick's diffusion equation. The effective diffusivity coefficients were estimated to be

from $3.76 \times 10^{-11} \text{ m}^2/\text{s}$ to $8.46 \times 10^{-11} \text{ m}^2/\text{s}$ for the entire range of the experimental data with R^2 above 0.96. For the process, the activation energy was calculated as 11.03 kJ/mol assuming an Arrhenius type temperature reliance.

Nomenclature

M	– moisture content of canola at any time (kg of moisture/kg of dry solid)
M_i	– initial moisture content of canola (kg of moisture/kg of dry solid)
M_e	– equilibrium moisture content of canola (kg of moisture/kg of dry solid)
D_{eff}	– effective diffusion coefficient (m^2/s)
D_o	– pre-exponential factor of Arrhenius equation for effective
E_a	– activation energy (kJ/mol)
MR	– Moisture Ratio diffusion coefficient
$MR_{\text{exp. } i}$	– i^{th} experimental moisture ratio
$MR_{\text{pre. } i}$	– i^{th} predicted moisture ratio
R^2	– coefficient of determination
X^2	– reduced mean square of the deviation
RMSE	– root mean square error
r	– canola radius (m)
T	– temperature (K)
t	– time (s)
N	– number of observations
n	– number of the drying model constants
a, b, k	– constants of the drying models

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