Thin Layer Drying and Equilibrium Moisture Content Equations for Canola (*Brassica napus L.*)

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ABSTRACT- A fully instrumented air conditioning laboratory unit capable of controlling drying air temperature and humidity integrated with an instantaneous weighing thin layer drying system was used to investigate the thin layer drying behavior and desorption equilibrium moisture content of canola (*Brassica napus L.*). To this aim, freshly harvested canola samples with moisture content of about 12±0.5% (d.b.) were dried at temperature levels of 40, 45, 50, 55 °C and absolute air humidity levels of 0.005, 0.01, 0.015, and 0.02 kg/kg. The instantaneous grain moisture content was measured by weighing the sample periodically. Drying was continued until canola kernels reached a constant weight to obtain the hygroscopic equilibrium moisture for different combinations of drying air temperature and absolute humidity. To select a suitable model for describing the thin layer drying of canola, experimental drying data were fitted with three thin layer drying models, namely, Page, Modified Page and Two-Term Exponential models. Furthermore, four widely used desorption isotherm models including Chung-Pfost, Modified Chung–Pfost, Modified Oswin, and Modified Smith were used to fit the experimental data of equilibrium moisture content. Finally, non-linear regression analyses were run and based on the highest value for R^2 and the lowest value for χ^2, mean bias error (MBE) and root mean square error (RMSE), the most suitable models for thin layer drying and equilibrium moisture content were determined to be Two-Term Exponential and Modified Smith, respectively.

Keywords: Canola, Drying, Equilibrium moisture content, Thin layer

Nomenclature

M moisture content of grain, decimal d.b., kg/kg

M_{in} initial moisture content of grain, decimal d.b., kg/kg

M_e equilibrium moisture content, decimal d.b., kg/kg

MR dimensionless moisture ratio

t drying time, min

T drying air temperature, °C

H absolute air humidity, kg/kg

k, n, a, b, k_1, k_2 drying model constants

N number of observations

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Z   number of model constants

Subscripts

exp   experimental data

pre   predicted data

INTRODUCTION

Canola seeds are used to produce edible oil that is suitable for human consumption. Canola oil is the world's third largest source of vegetable oil accounting for 13% of the world's vegetable oils, followed by soybean oil 32%, and palm oil 28% (6). Canola is harvested at moisture content of 12-13% (w.b.) approximately, but for oil extraction or storage of this product, the moisture content has to be decreased to 6-7% (w.b.). Drying is a post-harvest process that not only consumes a considerable amount of energy but also affects product quality. One of the cheapest and most efficient methods to design a new dryer or improve current dryers is the simulation of the drying process. In this way, the designer can look inside the dryer prior to manufacturing it and access information about the drying process.

The generalized thin layer drying equation is an essential element to solve the coupled heat and mass transfer simulation models. On the other hand, knowledge about the equilibrium moisture characteristics is essential regarding stability in storage and acceptability of grains, drying process modeling, design and optimization of drying equipment, aeration, calculation of moisture changes which may occur during storage and selection of appropriate packaging materials (1, 7, 20 and 26). Various simulation models have been developed for thin-layer drying of grain and oil seeds such as soybean (19), rough rice (2), barley (5) and wheat (17). Furthermore, several equations have been used by investigators to describe the moisture isotherms of food and agricultural materials. The four commonly used equations were Chung-Pfost and Modified Chung-Pfost model, Modified Smith, and Modified Oswin model (3, 24 and 28). To the authors' knowledge, the limited research conducted in this area either concerns thin layer drying and equilibrium moisture content of canola which are not generalized in terms of drying parameters including temperature and absolute humidity (9 and 22), or is limited to ambient conditions rather than drying conditions (13 and 23). It is not possible, therefore, to apply the results of such studies for simulation of drying process of canola. Above that, in all previous studies regarding other agricultural products or foodstuffs, the thin layer drying equation as well as the equilibrium moisture content were formulated with temperature and relative humidity variables which naturally correlate together (2, 3, 13, 16, 24 and 28). However, an equation must be obtained from independent variables to draw out their independent effects on moisture prediction, an important matter not considered by many researchers. A mathematical modeling obtained based on temperature and absolute humidity of drying air (i.e. two independent parameters) can help designers and engineers to access the exact effect of each parameter on equilibrium moisture content. Therefore, the objective of this study is to obtain the generalized equations of thin layer drying and equilibrium moisture content based on drying air temperature and absolute humidity.

MATERIALS AND METHODS

Experimental apparatus and procedure

A fully instrumented Hilton Air Conditioning Laboratory Unit capable of controlling drying air temperature and humidity was used. The apparatus has two main sections including an air conditioning and a drying section, shown in Fig. 1.
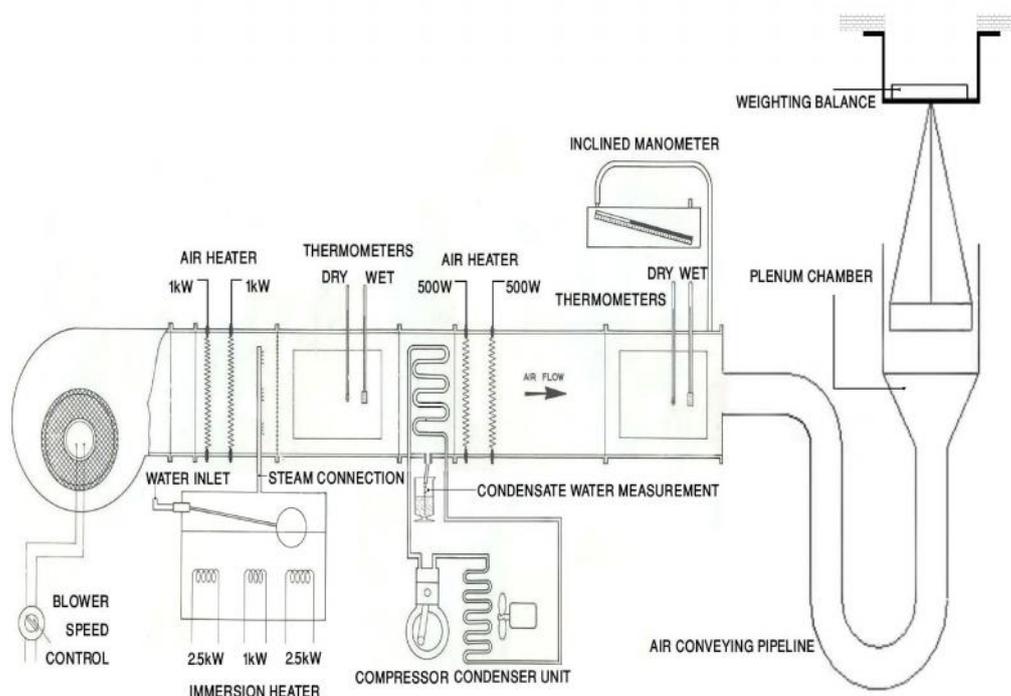
Fig. 1. Schematic layout of the Hilton Air Conditioning Laboratory Unit integrated with a thin layer dryer system

The air conditioning section of the experimental apparatus consisted of a fan with variable speed control, two air pre-heaters of 1 kW, three immersion heaters (2.5, 1, 2.5 kW) with a steam connection inserted into the air duct which forms a steam injection section, a cooling coil and two air after-heaters of 0.5 kW. Power input of all heaters could be controlled separately. Voltage supply to one of the air pre-heaters and one of the air after-heaters was regulated by manually controlled dimmer states in order to keep drying temperatures constant. The drying section of the apparatus had a circular drying tray, 20cm in diameter with a capacity of 200g, on which canola were fully exposed to the air stream in thin-layer form. The tray holding the sample was suspended under the weighing balance (GF-600, ±0.001g) during the tests. The air stream was uniform in temperature and humidity. Moreover, to ensure the uniformity of air velocity distribution at the bed section, air was passed through a distributor prior to approaching the bed. For measuring and controlling air temperature and humidity a digital temperature and humidity meter -Testo 625- with an accuracy of ±0.5°C and range of -10 to 60°C and ±2.5% RH ranging from 0 to 100% was used. The air velocity was measured using a digital anemometer -Testo 425- with an accuracy of ±0.03 m/s. In all experiments air velocity was kept constant at 0.4± 0.1m/s.

For each treatment about 100 g canola with initial moisture content of about 12% w.b., was kept in plastic bags and stored in a cold chamber at a temperature of approximately 5°C. Samples were taken out of the chamber about 4 hours prior to each drying test, so that they reached thermal equilibrium with ambient conditions. Drying experiments were performed at 40, 45, 50, and 55 °C air temperatures. At each temperature level the air absolute humidity was set at 0.005, 0.01, 0.015, 0.02 kg/kg. The weight reduction of samples was measured regularly during the drying process in less than 30 s. To eliminate measuring fluctuations, the air direction was changed using a lid to avoid reaching the hanging sample holder during weighing. The drying continued until the samples reached a constant weight to obtain the hygroscopic equilibrium moisture for different combinations of drying air temperature and absolute humidity. Three measurements were done for each drying condition.

Drying models

The moisture ratio of samples during drying can be expressed by the following equation (11 and 15):

$$MR = \frac{M - M_e}{M_{in} - M_e} \tag{1}$$

To select a suitable model for describing the drying process of canola, drying curves were fitted with three thin layer drying equations (Table 1).

Table 1. Mathematical models applied to the moisture ratio values

Equation No	Model name	Model	Ref.
1	Page	$MR = \exp(Kt^n)$	(11)
2	Modified Page	$MR = \exp(Kt)^n$	(19 and 27)
3	Two-Term Exponential	$MR = a\exp(-K_1 t) + b\exp(-K_2 t)$	(21)

Furthermore, four widely used desorption isotherm models, namely, Chung-Pfost, Modified Chung–Pfost, Modified Oswin, and Modified Smith were used to fit the measured values of the equilibrium moisture content during drying process (Table 2.).

Table 2. Mathematical models applied to the equilibrium moisture content

Equation No	Model name	Model	Ref.
1	Chung-Pfost	$M_e = E - F Ln(-(T+C)Ln(H))$	(8)
2	Modified Chung-Pfost	$M_e = -\frac{1}{c} Ln\left[\frac{(T+)Ln(H)}{-a}\right]$	(18)
3	Modified Smith	$M_e = (a+bT) - (c+dT)Ln(1-H)$	(24)
4	Modified Oswin	$M_e = (a+bT)\left(\frac{H}{1-H}\right)$	(1, 7 and 18)

The constants in the models were determined and correlated to drying air temperature and absolute humidity by non-linear regression using SPSS 16 software. The coefficient of determination (R^2) was one of the main criteria for selecting the best model. In addition, the goodness of fitting was determined by various statistical parameters such as reduced chi-square, χ^2, mean bias error (MBE) and root mean

square error (RMSE). In acceptable fitness, the value of R^2 should be higher and χ^2, MBE and RMSE values should be lower (10, 12, 13 and 25). The parameters were calculated by the following equations:

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{\exp} - MR_{pre}\right)^2}{N-Z} \tag{2}$$

$$MBE = \frac{1}{N}\sum_{i=1}^{N}\left(MR_{\exp} - MR_{pre}\right) \tag{3}$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{\exp} - MR_{pre}\right)^2\right]^{\frac{1}{2}} \tag{4}$$

RESULTS AND DISCUSSION

The moisture ratio of canola dried at different air temperatures and absolute humidity were fitted into the thin layer drying models (Table 1). Furthermore, the experimental equilibrium moisture content data were fitted with the stated desorption isotherm models (Table 2). The corresponding constants in the thin layer and desorption models, the coefficient of determination and results of statistical analyses are given in Tables 3 and 4. In all cases, R^2 values for the mathematical models were greater than 0.95, indicating a good fit. Based on the highest R^2 and lowest χ^2, mean bias error (MBE) and root mean square error (RMSE), the most suitable models for thin layer drying and equilibrium moisture were found to be Two-Term Exponential and Modified Smith, respectively. Gazor (13) showed that the Modified Oswin and Modified Chung-Pfost models had good fitting with experimental data of equilibrium moisture content of canola at 30, 40, 50 and 60 °C. However, the best model might be selected based on its simplicity.

Table 3. Statistical results of mathematical modeling of desorption equations

Model name	Model constants	R2	X2	MBE	RMSE	Pvalue
Page	K=0.069+0.034Ln(T)-0.658H n=1.684-0.256Ln(T)+6.45H	0.97	0.00251	-0.0065	0.04963	<0.0001
Modified Page	K=0.026-0.241H n=1.309-0.014Ln(T)+7.49H	0.973	0.002268	-0.0061	0.04717	<0.0001
Two-Term Exponential	a=2.834-0.563LN(T)+8.752H K=0.079-0.018Ln(T)+0.011H b=-1.83+0.562Ln(T) – 8.978H k₂=-0.542+0.188Ln(T) – 1. 38H	0.979	0.00176	0.00215	0.04117	<0.0001

The experimental versus predicted data of moisture ratio for the Two-Term Exponential model are illustrated in Fig 2 which emphasizes the suitability of the model for describing the thin layer drying process of canola seeds. The results showed that both temperature and absolute humidity of the drying air have considerable effect on drying duration.

To determine the effect of the drying air temperature on the drying behavior of canola seeds the drying curves are plotted for different levels of drying air temperature at constant drying air absolute humidity of 0.01kg/kg (Fig 3). The same trends were obtained for other treatments. It can be seen that higher levels of drying air temperature lead in less drying time. This is due to higher rate of moisture migration inside canola seeds. Similar results are reported by other studies (2, 5, 17, and 19).

Table 4. Statistical results of mathematical modeling of equilibrium moisture content

Model name	Model constants	R2	X2	MBE	RMSE	Pvalue
Chung-Pfost	**E=0.218, F=0.032, C=-29.6**	**0.947**	8.8×10^{-6}	2.6×10^{-12}	**0.0027**	**<0.0001**
Modified Chung-Pfost	**a=6.0, b=18.36, c=44.29**	**0.947**	8.7×10^{-6}	6.7×10^{-11}	**0.0027**	**<0.0001**
Modified Smith	**a=0.134, b=-0.001, c=2.967, d=-0.049**	**0.972**	5.06×10^{-6}	-2.41×10^{-9}	**0.002**	**<0.0001**
Modified Oswin	**a=0.249, b=-0.003, c=0.083**	**0.951**	8×10^{-6}	6.9×10^{-6}	**0.0025**	**<0.0001**
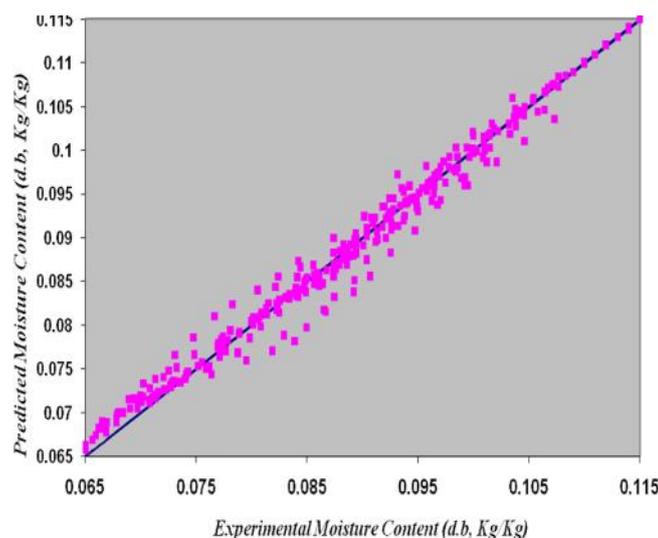
Fig. 2. The experimental data versus predicted data for Two-Term Exponential model

The variations of moisture content of canola during drying at a constant level of drying air temperature are shown in Fig 4. The drying time decreases when the absolute humidity of the drying air reduces, due to the increase in the difference between water vapor pressure of the air stream and canola seeds. The same trends were obtained for other treatments.

The experimental data and those predicted by the Modified Smith model are presented in Fig 5. According to the results, the temperature and absolute air humidity have considerable effect on equilibrium moisture content. As the drying air temperature increases, the desorption equilibrium moisture content of canola decreases. This might be due to a rise in the energy level of water molecules inside the grains. This can result in a decline in the stability of water molecules located in the water binding site of canola seeds. As a result, the monolayer moisture content

decreases. An increase in drying air humidity at a constant air temperature leads in an upward trend in the value of the equilibrium moisture content. Such results have been previously reported by other researchers (4, 7, 13 and 14).
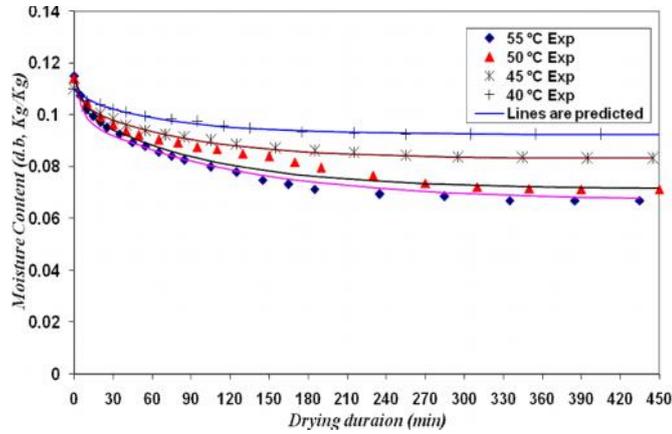

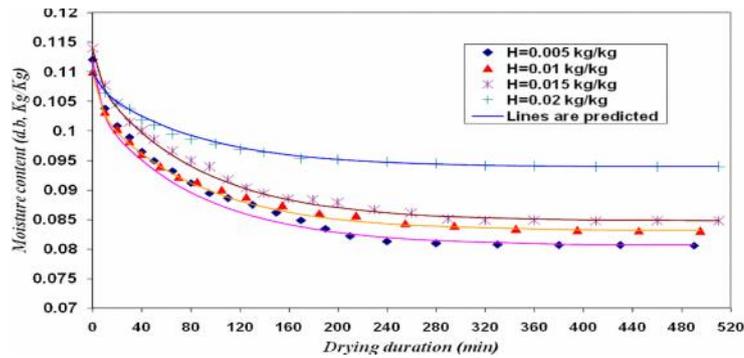**Fig. 3. The drying trend for different drying air temperatures at constant absolute humidity of 0.01Kg/Kg**

Fig. 4. The drying trend of canola for different drying air humidity levels at constant air temperature of 45°C
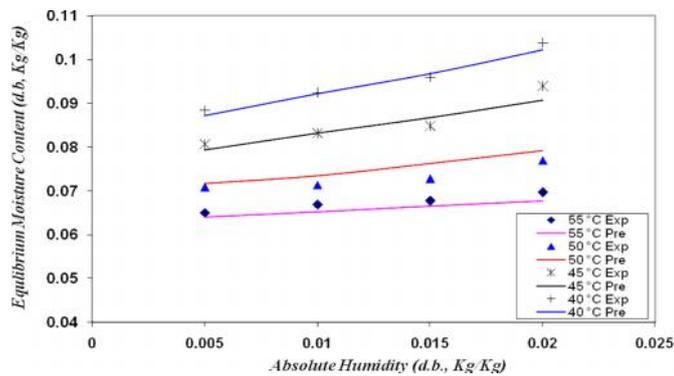

Fig. 5. The isotherm equilibrium moisture content of experimental data and those predicted by the modified Smith model

CONCLUSIONS

Thin layer drying of canola was modeled based on temperature and absolute humidity of drying air, both independent drying parameters. Such method of modeling can help the designers of dryers to find the exact effect of each parameter on the drying behavior of grains. The most suitable model for thin layer drying and equilibrium moisture were Two-Term Exponential and Modified Smith models, respectively. Moreover, it was found that increasing the drying temperature or decreasing the drying humidity resulted in a reduction of the drying time.

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تعیین معادله لایه نازک و رطوبت تعادلی کلزا

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چکیده - به منظور بررسی رفتار خشک شدن لایه نازک و همچنین دستیابی به رطوبت تعادلی خشک شدن کلزا از دستگاه هوا ساز آزمایشگاهی مجهز به سیستم خشک کن لایه نازک و سنجش وزن لحظه ای که قابلیت کنترل دما و رطوبت مطلق هوا را داشت استفاده شد. به منظور دستیابی به اهداف طرح، کلزای تازه برداشت شده با رطوبت اولیه ٪12±0/5 وزن خشک در ترکیب ۴ سطح دما ($^\circ$C ۵۵،۵۰ ،۴۵،۴۰) و ۴ سطح رطوبت مطلق هوا (kg/kg ۰/۰۲، ۰/۰۱۵، ۰/۰۱، ۰/۰۰۵) خشک گردید. رطوبت لحظه ای محصول در طی فرایند خشک شدن به کمک توزین دوره ای نمونه ها ثبت گردید. برای تعیین رطوبت تعادلی، خشک شدن تا زمانی ادامه یافت که محصول در شرایط مختلف دما و رطوبت مطلق هوا به تعادل برسد. برای انتخاب بهترین مدل خشک شدن لایه نازک کلزا داده های تجربی با سه مدل معروف پیج، پیج اصلاح شده و مدل درجه ۲ نمایی تطبیق داده شدند. علاوه بر آن برای تعیین مدل رطوبت تعادلی در محدوده خشک شدن از چهار مدل چانگ پی فاست، چانگ پی فاست اصلاح شده، اسوین اصلاح شده و اسمیت اصلاح شده استفاده شد. در نهایت به کمک رگرسیون غیر خطی و بر اساس بالاترین مقدار ضریب تعیین و کمترین مقدار شاخص کای دو، خطای میانگین و ریشه خطای میانگین   مناسب ترین مدل برای خشک شدن لایه نازک و رطوبت تعادلی به ترتیب مدل دو جمله ای نمایی و مدل اصلاح شده اسمیت معرفی شدند.

واژه های کلیدی: ، خشک شدن، رطوبت تعادلی، کلزا، لایه نازک