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Drying Characteristics of Palm Kernel Cake in a Radial Flow Packed Bed

Hooi-Kim Phang, Sivakumar Kumaresan and Chi-Ming Chu
Materials and Mineral Research Unit, School of Engineering and Information Technology,
Universiti Malaysia Sabah, Jalan UMS, 88400 Kota Kinabalu, Sabah, Malaysia

Abstract: The drying characteristics of Palm Kernel Cake (PKC) were investigated in a radial flow packed bed to understand the transfer processes in Solid State Fermentation (SSF). The 1.50 mm Palm Kernel Cake (PKC) particles with an initial moisture content of 50% on dry basis (d.b) was the filler material. The drying experiments were conducted using heated ambient air for four air temperatures (35, 45, 55 and 65°C) and three air flows (65.33, 75.33 and 92.33 LPM) in a laboratory radial flow packed bed. The drying data were then fitted to the different semi-theoretical models such as Lewis, Page, modified Page, logarithmic and Henderson and Pabis based on the ratio of the difference between the initial, final moisture content and the equilibrium moisture content. The models were evaluated by comparing the determination coefficient (R^2) and Root Mean Square Error (RMSE) through non linear regression analysis. The drying air temperature was found to be the dominant factor affecting the drying kinetics of PKC.

Key words: Palm kernel cake, drying kinetics, radial packed bed

INTRODUCTION

Palm kernel cake (PKC) is a byproduct produced by palm oil industry in Malaysia. It is obtained whether by mechanical (expeller) or solvent process. In 2011, Malaysia produced 2.39 million tonnes of PKC and exported 2.23 million tonnes to the international market. The major PKC export markets were the European Union countries (39.5%), followed by New Zealand and South Korea. Mechanical extraction by screw press is the most common practice in Malaysia and PKC also referred as palm kernel expeller (Tang, 2001).

PKC contains no toxins, aflatoxin free and palatable (Sundu *et al*., 2006) and has been implemented as a substrate in Solid State Fermentation (SSF) for enzyme and animal feed production in various types of bioreactor. In SSF processes, the bioreactors are designed to provide favourable conditions for the growth of microorganism as well as the product formation. The water in the solid particles is evaporated through conduction and convection using air flow by a forced aeration system (Abdeshahian *et al*., 2010; Phang *et al*., 2009; Abd-Aziz *et al*., 2008). Thus, the moisture content and temperature of the bed are the two important process parameters for modelling and optimization. The modelling and optimization of SSF process on temperature and moisture content should be microorganism strain and bioreactor specifically (Fanaei and Vaziri, 2009; Khanahmadi *et al*., 2006; Hamidi-Esfahani *et al*., 2004). The drying characteristic of non-fermented PKC in a specifically bioreactor is essentially required prior to SSF process as a first step to modelling and optimizing the product formation of SSF of PKC. Hence, the influence of air temperature and air flow rate on the drying of non-fermented PKC in a radial packed bed was investigated in this study.

MATERIALS AND METHODS

Drying system: A batch-type packed bed was designed and fabricated where the A schematic diagram of the laboratory set up is illustrated in Fig. 1. The reactor consists of three sections: an air flow control system (Cole Parmer flow meter 10-100 LPM, model EW-32461-20), a heating control system (Memmert water bath, model WB 14) and a data acquisition system (Cole Parmer USB data acquisition module, model 18200-40). The control air flow was introduced to the packed bed by an air compressor (Hitachi Oil free Bebicon, 1HP) through an inner pipe distributor. The air flow rate and the air temperature in the system were varied by controlling the regulator of rotameter and water bath temperature of heating system. The ambient air was heated while flowing through the heating system. The K-type thermocouples were used to measure the ambient and inlet of air temperature.

Corresponding Author: Sivakumar Kumaresan, Materials and Mineral Research Unit,
School of Engineering and Information Technology, Universiti Malaysia Sabah, Jalan UMS,
88400 Kota Kinabalu, Sabah, Malaysia Tel: +60-88-320000 ext 3315 Fax: +60-88-320348

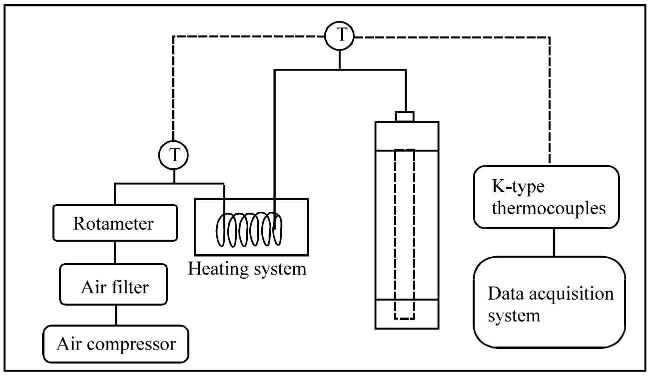

Fig. 1: Experimental set up of laboratory dryer

Table 1: The drying curve models evaluated in this study

Model	Analytical expression	Reference
Lewis	$MR = \exp(-kt)$	Lewis (1921)
Henderson and pabis	$MR = a \exp(-kt)$	Henderson and Pabis (1961)
Logarithmic	$MR = \exp(-kt)+c$	Togrul and Pehlivan (2004)
Page	$MR = \exp(-kt^n)$	Page (1949)
Modified page	$MR = \exp(-kt)^n$	Page (1949)

Experimental procedure: Experiments were conducted to determine the influence of air temperature and air flow rate on the drying characteristics of PKC in a laboratory radial flow packed bed. The raw PKC was mechanically sieved with a sieving vibrator (UTS Unit Test, 240 V) as reported by Saw *et al.* (2012a) for particle distribution. 385 mL of water was added into 770 g of 1.50 mm dried PKC for 50% moisture content in dry basis (d.b), well mixed and then left for 10 min for maximum swelling (Saw *et al*., 2008). The moist PKC was then loaded into packed bed by hydrating, loading and tapping (HLT) method (Saw *et al*., 2012b). The drying characteristic of PKC were studied in the packed bed under heated air temperature of 35, 45, 55 and 65°C and air flow rates of 65.33, 75.33 and 92.33 LPM at atmospheric pressure. The sample was withdrawn and moisture content was analyzed every 1.5 h by offline measurement (inside an oven at 105°C for 24 h). All the experiments were done in duplicate.

Mathematical modelling of drying curves: The drying data was modeled to investigate the drying characteristics of PKC. The drying data was expressed as Moisture Ratio (MR) versus drying time (t) for all air temperatures and air flow rate at the three positions of radial packed bed. The dimensionless Moisture Ratio (MR) is the ratio of the difference between the initial, final moisture content and the equilibrium moisture content where:

$$MR = \frac{M_t - M_e}{M_0 - M_e}$$

where, M_t is the moisture content at any time, M_0 is the initial moisture content and M_e is the equilibrium moisture content. The selected drying models as shown in Table 1 were fitted to all the experimental data based on MR. The goodness of fit of the models was evaluated based on coefficient of determination (R^2) and Root Mean Square Error (RMSE) by relating the experimental and predicted moisture ratio through non linear regression technique.

RESULTS AND DISCUSSION

The parameter value of drying models for air temperature of 35, 45, 55 and 65°C and air flow rate of 65.33, 75.33 and 92.33 LPM undertaken by non linear regression technique on the five models as listed in Table 1 are listed in Table 2. The goodness of fit of drying models to experimental data was evaluated by coefficient of determination (R^2) and RMSE values. The R^2 and RMSE vary between 0.8847-0.9917, 0.9491-0.9925 and 0.0310-0.1119, 0.0276-0.0716 for 75.33 and 92.33 LPM, respectively. It was found that all the models fitted the experimental data better at higher air flow rate and had lowest RMSE if compared to the lower air flow rate. Although the results shows that the highest values of R^2 and the lowest values of RMSE were obtained by Page model, the goodness of fitting results indicated that the other models fitted the experimental data of moisture ratio satisfactorily. The Henderson and Pabis model, which is a simple model with two parameters (a and k), was chosen to fit the experimental data.

The effect of drying air temperature at air flow rate of 65.33 LPM on drying curves is presented in Fig. 2. The drying curves for 75.33 and 92.33 LPM air flow rate also had the similar trend. The moisture ratio decreased exponentially with the increased of drying time. Furthermore, the drying curves was decreased significantly with the increased of air temperature. It was

Table 2: Drying models parameter values

Model	Temp. (°C)	Model constant	R^2	RMSE
65.33 LPM				
Lewis	35	k = 0.1422	0.7301	0.1545
	65	k = 0.3792	0.9707	0.0609
Henderson and	35	k = 0.1623, a = 1.1292	0.8175	0.1431
Pabis	65	k = 0.3726, a = 0.9732	0.9688	0.0567
Logarithmic	35	k = 0.0061, a = 16.8118, c = -15.7368	0.9252	0.0977
	65	k = 0.4032, a = 0.9546, c = 0.0252	0.9689	0.0560
Page	35	k = 0.0106, n = 2.4044	0.9575	0.0752
	65	k = 0.4846, n = 0.8105	0.9745	0.0503
Modified page	35	k = 0.3771, n = 0.3771	0.7301	0.1545
	65	k = 0.6186, n = 0.6186	0.9696	0.0577
75.33 LPM				
Lewis	35	k = 0.1788	0.9866	0.0323
	65	k = 0.4031	0.9238	0.0941
Henderson and Pabis	35	k = 0.1823, a = 1.0170	0.9878	0.0315
	65	k = 0.3757, a = 0.9370	0.9182	0.0909
Logarithmic	35	k = 0.1778, a = 1.0276, c = -0.0125	0.9879	0.0315
	65	k = 0.5047, a = 0.8888, c = 0.0754	0.9217	0.0865
Page	35	k = 0.1612, n = 1.0604	0.9882	0.0310
	65	k = 0.6733, n = 0.5930	0.9505	0.0681
Modified Page	35	k = 0.2060, n = 0.8683	0.9866	0.0323
	65	k = 0.4198, n = 0.9602	0.9238	0.0941
92.33 LPM				
Lewis	35	k = 0.2140	0.9654	0.0554
	65	k = 0.4394	0.9867	0.0383
Henderson and pabis	35	k = 0.2100, a = 0.9824	0.9644	0.0550
	65	k = 0.4316, a = 0.9817	0.9867	0.0376
Logarithmic	35	k = 0.1828, a = 1.0356, c = -0.0637	0.9664	0.0539
	65	k = 0.5042, a = 0.9463, c = 0.0469	0.9907	0.0307
Page	35	k = 0.2228, n = 0.9756	0.9649	0.0553
	65	k = 0.5488, n = 0.7989	0.9925	0.0276
Modified page	35	k = 0.4626, n = 0.4626	0.9654	0.0554
	65	k = 0.6629, n = 0.6629	0.9867	0.0383

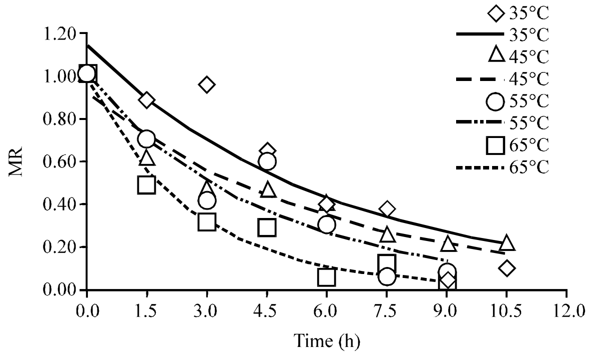

Fig. 2: Drying curves of PKC at different temperatures for 65.33 LPM air flow rate

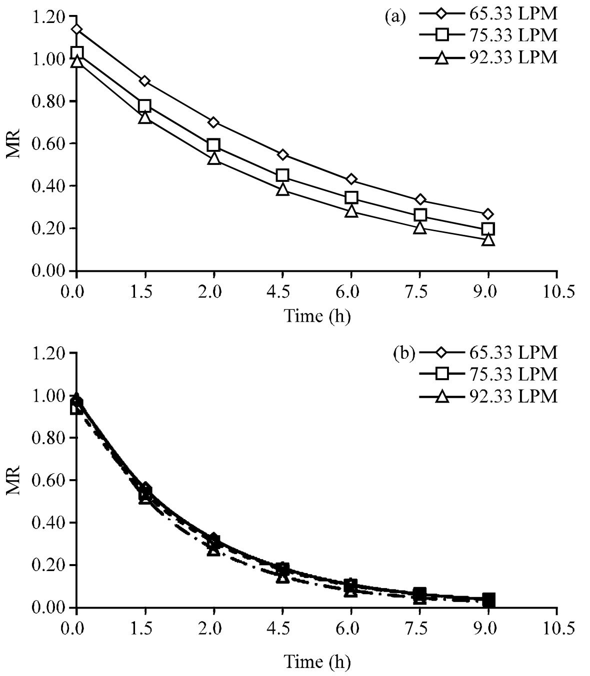

Fig. 3(a-b): Air flow rate effect on the drying for air temperature of (a) 35°C and (b) 65°C

found that the drying process occurred in the falling rate period only. This implies that the drying process was governed by diffusion mechanism (Celma *et al*., 2008; Gunhan *et al*., 2005).

The effect of air flow rate on drying was found to be insignificant compared to drying air temperature as shown in Fig. 3. Some researchers also neglect the effect of air flow rate where assumed that the resistance to moisture movement is relies more on internal resistance than the surface to the drying medium (Celma *et al*., 2008;

Gunhan *et al*., 2005; Madamba *et al.,* 1996). Thus, the effect of air flow rate variation can be neglected for air temperature higher than 65°C since the air flow rate had no effect on the drying. This implies that the evaporation of water at low temperature initially take place at the surface and gradually the move towards the interior of the solid where the moisture diffusion becomes dominant process. However, the evaporation of water at high temperature is purely depends on the internal resistance of moisture movement.

CONCLUSION

Five drying models were fitted to the experimental data of PKC drying and the mathematical modelling was evaluated using a non linear regression method. The Henderson and Pabis model (MR= a exp (-kt) is adequate to describe the change of moisture ratio with drying time within a temperature range of 35 to 65°C and air flow rate range of 65.33 to 92.33 LPM as it is simple with a reasonably high coefficient of determination, R^2 and low RMSE as compared to the other more complex models.

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