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THIN LAYER MODELS FOR SPONGE MEDIA DRYING

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ABSTRACT

Sponge media blasting has become popular among industries which require surface preparation such as equipment and machineries refurbishing, oil and gas structure fabrication and many more. However, sponge media requires a rapid drying system when operating in a wet surrounding. This paper presents modeling of the drying kinetics of sponge media when dried in a swirling fluidized bed dryer (SFBD). Five widely used semi-empirical models were adapted from the literature namely Logarithmic model, Henderson and Pabis model, Modified Henderson and Pabis model, Newton or Lawis model and Verma *et al.* model. Batch drying was conducted for three bed weights of 0.5, 0.75 and 1.0 kg at three drying temperatures of 80 ºC, 90 ºC and 100 ºC. The experimental data from experiments was fitted to these models before anayzed statistically. It was found that Verma *et al.* model gave the best fit among the five models with a correlation coefficient of 0.98774 and having lowest root mean square error, RMSE, (0.05049), residuals (0.34423) and reduced chi-square, χ^2, (0.002549).

Keywords: sponge media, swirling fluidized bed dryer, semi-empirical modelling, statistical analysis.

INTRODUCTION

Surface preparation is crucial in many sectors particularly which requires structural integrity for safe operation. Recently, the usage of sponge media as blasting material has gained interest among many industries such as heavy equipment and machinery refurbishing, oil and gas structure fabrication and many more. The blasting process using sponge media gives a dry, low dust process that requires minimal containment, reduces downtime and can be reused, in contrast to the conventional abrasive blasting. The sponge media blasting requires the use of clean and dry sponge in the process. However, problem arises when the used sponge media were subjected to a high humidity surrounding or soaked in water especially during rainy seasons. This has always been a challenge to the industries to overcome and the companies constantly seek for a reliable drying technology with reasonable cost. Conventional drying methods such as drying under the sun or the usage of large industrial fans to improve evaporation rate were neither practical nor feasible and as they require more logistics and drying time. Furthermore, these methods also depends daily weather conditions.

Recently, the swirling fluidized bed dryer (SFBD) were proposed by Zakaria *et al.,* 2014 as an alternative method in drying of wet sponge media. The SFBD system was reported to have rapid moisture removal capability and flexibility to operate over a wide range of particle size. The SFBD is capable in providing both vertical and horizontal momentum inside the bed which allows vigorous mixing and high degree of solid-gas contact which is ideal for processes such as drying (Mohideen *et al.*, 2012a). This paper reports the utilization of several well known thin layer drying models in predicting the drying kinetics of sponge media in a SFBD system, namely Logarithmic model, Henderson and Pabis model, Modified Henderson and Pabis model, Newton or Lawis model and Verma *et al.* Model. To determine the best model in predicting the drying curves, statistical analysis was carried out using four statistical parameters, namely correlation coefficient (R^2), root mean square error (RMSE), reduced chi-square (χ^2) and residuals to determine the best model that fits the drying curve. The findings will be useful in designing an actual industrial scale SFBD system as sought in the industry.

METHODOLOGY

Description of experimental set-up

The experimental study was initially carried out in the SFBD system and reported by Zakaria *et al.,* 2014. The SFBD system was made by an array of 60 blades which resembles a stator configuration in a gas turbine system. These blades which were inclined at 12° from the horizontal plane form an annular bed as a centre body is placed in the core of the system as depicted in Figure-1.

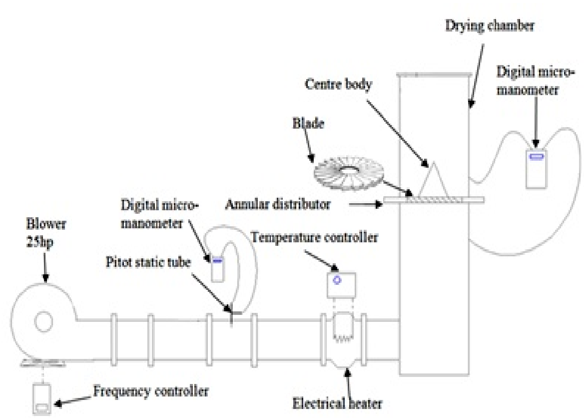

Figure-1. Schematics of the experimental set-up.

The particles have an average diameter of 4.514 mm. Three bed loadings of 0.5 kg, 0.75 kg and 1.0 kg were studied and other details of experiments can be found

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elsewhere. The centre body was necessary to avoid dead zone in the bed (Mohideen *et al.,* 2011). When hot air flows through the inclined distributor, two jet velocity components created in the bed; the vertical component which fluidizes the bed whiles the horizontal component which induces swirling. The magnitude of each component depends on the blade inclination. Lower blade angles were preferred as they provide larger horizontal momentum and hence faster swirling with reduced elutriation due to smaller vertical momentum (Mohideen *et al.,* 2012b). The advantage of using swirling flow in drying was reported by many researchers, among them were Ozbey and Soylemez, 2005. The authors reported that the moisture extraction rate and dryer efficiency were increased when swirl motion up to 5-25% and 38% when compared with non-swirl motion.

Thin layer modeling of drying curves

Linear regression analysis and curve fittng was performed on the experimental data using LAB Fit software. LAB Fit allows user defined equations and hence all five semi-emprical models used in the present study were defined in the software. Upon analysis, LAB Fit provides statistical data that provides the coefficient of determination (R^2), reduced chi-square (χ^2), root mean square error (RMSE) and residuals which allows determination of the best model in this study. Table-1 lists the drying models which were adapted from the literature:

Table-1. Drying models which are used in the present work (Madhiyanon *et al.,* 2009), (Doymaz, 2006), (Wang *et al.,* 2007).

Model name	Model	
Henderson and Pabis	$MR = a\exp(-kt)$	(1)
Logarithmic	$MR = a\exp(-kt)+b$	(2)
Modified Henderson and Pabis	$MR = a\exp(-kt) + b\exp(-gt) + c\exp(-ht)$	(3)
Newton or Lawis	$MR = \exp(-kt)$	(4)
Verma et al.	$MR = a\exp(-kt) + (1-a)\exp(-gt)$	(5)

Moisture ratio (MR) or can be defining as dimensionless of moisture content can be calculated by this equation:

$$MR = \frac{M(t) - M_{eq}}{M_o - M_{eq}} \quad (6)$$

Where M_o, M(t) and M_{eq} are initial, at any moment (t), and equilibrium moisture content, respectively. M_{eq} usually being neglected especially for drying at high temperature, which M_{eq} values normally zero. M_{eq} is extremely small compared with M_0 and M(t) as reported by Madhiyanon *et al*., 2009.

The effectiveness of model fit was evaluated via the statistical parameters as described before, aiming for high coefficient of determination (R^2) but low values of reduced chi-square (χ^2), root mean square error (RMSE) and residuals (Madhiyanon *et al.,* 2009), (Doymaz, 2006), (Wang *et al.,*2007). These parameters were expressed as:

$$\chi^2 = \frac{\sum_{i=1}^{N} (MR_{exp,}i - MR_{pre,}i)^2}{N-p} \quad (7)$$

$$RMSE = \left(\frac{1}{N}\sum_{i-1}^{N}(MR_{exp,}i - MR_{pre,}i)^2\right)^{1/2} \quad (8)$$

$$P = \frac{100}{N}\sum_{i-1}^{N}\frac{|MR_{exp,}i - MR_{pre,}i|}{MR_{exp}i} \quad (9)$$

$$Residuals = \sum_{i=1}^{N}(MR_{exp,}i - MR_{pre,}i) \quad (10)$$

where $MR_{exp,i}$ and $MR_{pre,i}$ are the experimental and predicted moisture ratios while the number of observations is N, and the number of constants is p. The value of R^2, RMSE, residuals and χ^2 for experimental and each model are noted which describe different analysis. R^2 is a correlation coefficient measurement of association for regression. RMSE describe how much dispersion exists in the regression line. The higher the R^2 and the lower the RMSE, χ^2 and residuals the better the model fit.

RESULT AND DISCUSSION

Figure-2 below presents the experimental data for all the experiments carried out. The graph indicates that higher temperature of drying air reduces the drying time significantly. Higher drying temperatures were also found to have exponential decay curves which indicate the falling-rate type of drying, particularly for bed with lower loadings (0.5 kg and 0.75 kg). On the other hand, the drying curve for deep bed (1.0 kg) was found to have an almost linear trend. This may be attributed to the re-wetting effect due to the larger inventory of the bed, where the particles from the lower part of the bed transfer moisture to the particles at the upper part of the bed. Therefore a longer drying time was required for deep beds, apart from the larger amount of moisture content initially. For 0.5 kg with 100ºC air temperature for instance, the drying time was only 6 minutes while for 1.0 kg bed; the drying time was doubled to 12 minutes. In general, no constant rate drying period was observed in the present study.

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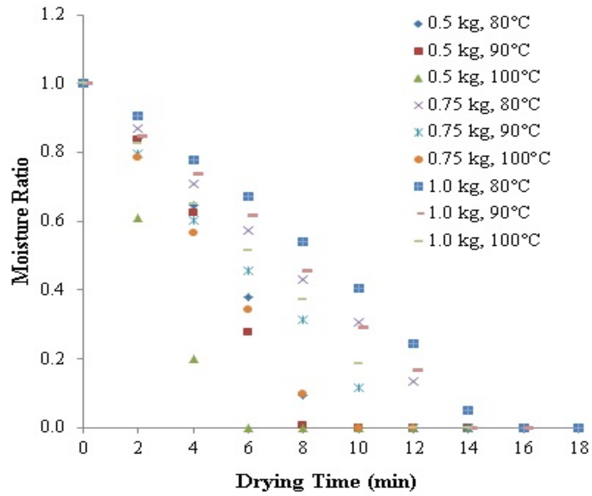
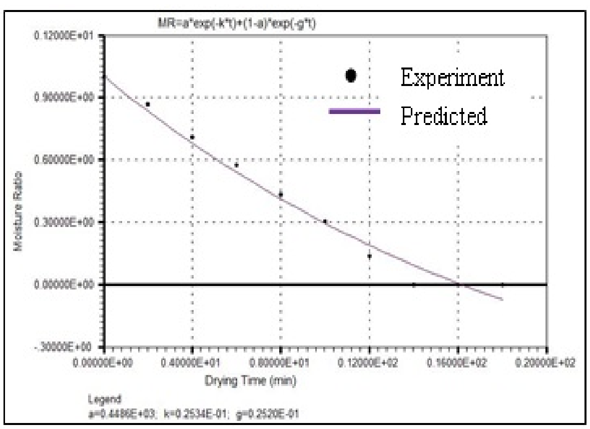
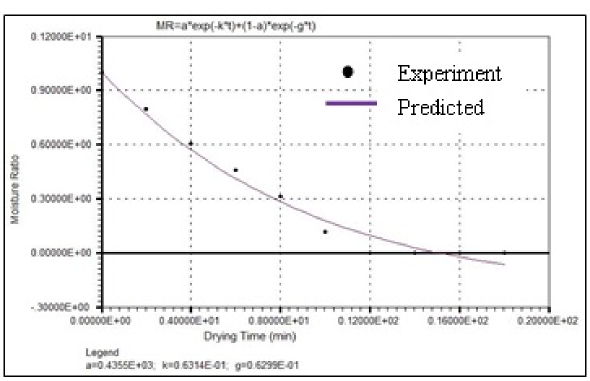


Figure-2. Experimental data obtained for three bed weight and three drying temperatures.

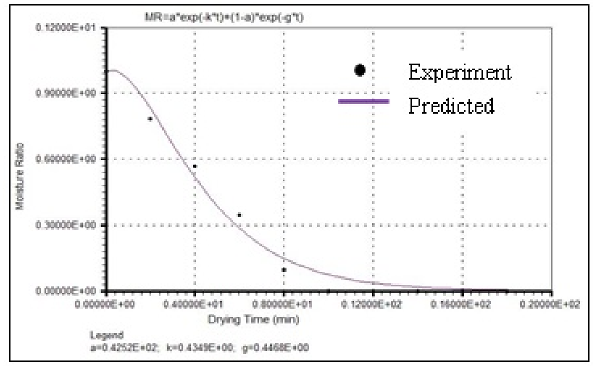
The results from thin-layer modeling obtained from LAB Fit were presented in the following figures with respect to the models used. However due to space limitation, only Verma et. al model and Logarithmic model was presented in Figure-3 and 4 respectively.



(a)

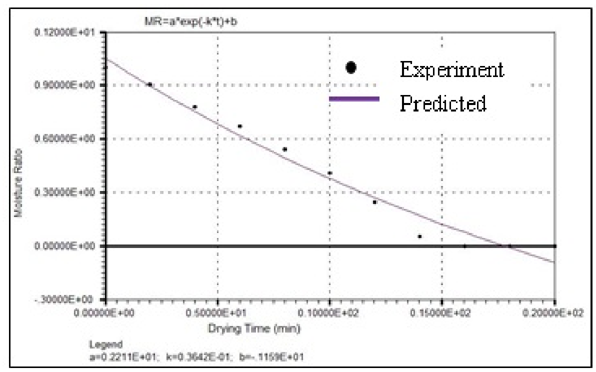


(b)

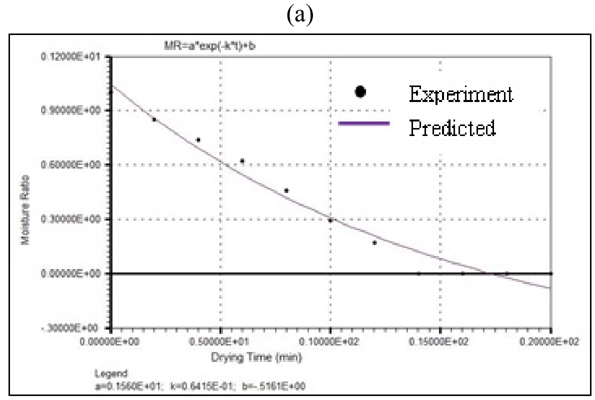


(c)

Figure-3. Comparison between experimental and predicted moisture ratio of Verma *et al.* model for 0.75 kg bed weight at a) 80 ºC, b) 90 ºC and c) 100 ºC.



(a)



(b)

Figure-4. Comparison between experimental and predicted moisture ratio of Logarithmic model for 1.0 kg bed weight at a) 80 ºC, b) 90 ºC and c) 100 ºC.

The two models, Verma *et al.* model and Logarithmic were presented here due to smaller difference between predicted and experimental data as compared to the other three models, indicating better ability of these two models in predicting moisture ratio change in the experiment.

Table-2, 3 and 4 summarizes the statistical analysis produced by non-linear regression analysis using

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LAB Fit software for the sponge media drying using SFBD system for all bed loading and temperatures.

Table-2. Sponge media linear regression data for 0.5 kg bed loading.

Bed Loading (kg)		0.5			
Model	**Temperature (°C)**	**R^2**	**RMSE**	**Residuals**	**χ^2**
Henderson and Pabis	80	0.93612	0.11283	0.91881	0.012729
	90	0.92816	0.11908	0.88086	0.014180
	100	0.97292	0.06337	0.38887	0.004016
Logarithmic	80	0.95095	0.09910	0.73602	0.009821
	90	0.93910	0.11093	0.78411	0.012306
	100	0.97412	0.06333	0.40249	0.004010
Modified Handerson and Pabis	80	0.93613	0.15956	0.91888	0.025461
	90	0.92815	0.16840	0.88082	0.028360
	100	0.97292	0.08962	0.38887	0.008032
Newton or Lawis	80	0.94285	0.11415	0.92329	0.013031
	90	0.93388	0.11946	0.87178	0.014271
	100	0.97361	0.06120	0.36750	0.003745
Verma et. al	80	0.95330	0.10148	0.70247	0.010299
	90	0.94255	0.11284	0.73669	0.012732
	100	0.97959	0.05778	0.35370	0.003339

Table-3. Sponge media linear regression data for 0.75 kg bed loading.

Bed Loading (kg)		0.75			
Model	**Temperature (°C)**	**R^2**	**RMSE**	**Residuals**	**χ^2**
Henderson and Pabis	80	0.94199	0.10240	0.85289	0.010486
	90	0.96047	0.08512	0.72298	0.007246
	100	0.95740	0.08924	0.73270	0.007963
Logarithmic	80	0.98479	0.05242	0.35350	0.002747
	90	0.98063	0.05856	0.43574	0.003429
	100	0.96819	0.07641	0.57656	0.005839
Modified Handerson and Pabis	80	0.94200	0.14483	0.85288	0.020975
	90	0.96046	0.12039	0.72301	0.014493
	100	0.95739	0.12621	0.73273	0.015928
Newton or Lawis	80	0.95176	0.10490	0.88824	0.011005
	90	0.96594	0.08514	0.73325	0.007249
	100	0.96192	0.08942	0.73015	0.007996
Verma et. al	80	0.98475	0.05413	0.35135	0.002930
	90	0.98200	0.05778	0.41487	0.003338
	100	0.98774	0.05049	0.34423	0.002549

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Table-4. Sponge media linear regression data for 1.0 kg bed loading.

Bed Loading (kg)		1.0			
Model	**Temperature (°C)**	**R^2**	**RMSE**	**Residuals**	**χ^2**
Henderson and Pabis	80	0.91913	0.12212	1.10800	0.014914
	90	0.93688	0.10712	0.94004	0.011475
	100	0.94974	0.09533	0.86684	0.009088
Logarithmic	80	0.97418	0.06898	0.53714	0.004759
	90	0.97461	0.06723	0.53028	0.004520
	100	0.97098	0.07119	0.56890	0.005069
Modified Handerson and Pabis	80	0.91912	0.16385	1.10802	0.026848
	90	0.93689	0.14372	0.94005	0.020657
	100	0.94971	0.12790	0.86687	0.016359
Newton or Lawis	80	0.93283	0.12716	1.19660	0.016171
	90	0.94675	0.10962	0.99154	0.012017
	100	0.95649	0.09645	0.89623	0.009302
Verma et. al	80	0.97328	0.07272	0.55921	0.005289
	90	0.97489	0.06880	0.52685	0.004733
	100	0.97257	0.07133	0.55446	0.005088

Based on the analysis, Verma *et al.* model and Logarithmic model produced the highest accuracy and repeatability. For 1.0 kg bed load, Logarithmic model produced the best curve fitting based on the statistical parameters for all drying temperature. Meanwhile, for 0.5 kg and 0.75 kg bed weight, Verma *et al.* model was found to predict the drying kinetics much better. Overall, the Verma *et al.* model produced the highest R^2 with 0.9877352 and the lowest RMSE (0.050488), residuals (0.344231) and χ^2 (0.0025490) and may be regarded as the best model for the present study.

CONCLUSIONS

The aim of this research was to study and to model by using semi empirical model drying kinetics of sponge media via SFBD drying and to fit them into five thin layer models. The moisture ratios of these models were calculated at three different temperatures which are 80, 90 and 100 ºC. The statistical analysis was obtained using non linear regression from LAB Fit software. The purpose of using non linear regression is to interpret the value of coefficient of determination (R^2), root mean square error (RMSE), reduced chi-square (χ^2) and residuals. The value of R^2 which mostly >0.99 considered as the accurate moisture ratio produced. Modelling drying curve for 0.75 kg at 100 ºC shows Verma *et. al.* model as the most precisely predictive model which gives R^2 = 0.98774 and the smallest value of RMSE, χ^2 and residuals. All these value will determine the accuracy and repeatability of moisture ratio for each model.

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REFERENCES

[1] Özbey, M and Söylemez, M S (2005) Effect of Swirling Flow on Fluidized Bed Drying of Wheat Grains, Energy Conversion and Management, Vol. 46 pp 1495-1512

[2] Doymaz, I. (2006), Thin-layer drying behavior of mint leaves, J. Food Eng., 74 370–375.

[3] Madhiyanon, A. Phila, S. Soponronnarit (2009), Models of fluidized bed drying for thin-layer chopped coconut, Applied Thermal Engineering, Vol. 29, No. 14-15, pp. 2849-2854.

[4] Mohideen, M. F., Faiz, M., Salleh, H., Zakaria, H., & Raghavan, V. R. (2011). Drying of oil palm frond via swirling fluidization technique. In Proceedings of the World Congress on Engineering (Vol. 3, No. 2011, pp. 2375-2380).

[5] Mohideen M F, Sreenivasan B, Sulaiman S A and Raghavan V R (2012a), Heat Transfer In A Swirling Fluidized Bed With Geldart Type-D Particles, Korean J. Chem. Eng., Vol. 29(7) 862-867.

[6] Mohideen M F, Md Seri S and Raghavan V R (2012b) Fluidization of Geldart Type-D Particles in a Swirling Fluidized Bed, Applied Mechanics and Material, Vols. 110-116:3720-3727

[7] Wang, Z.F., Sun, J.H., Liao, X.J., Chen, F., Zhao, G.H., Wu, J.H., Hu, X.S., (2007), Mathematical modelling on hot air drying of thin layer apple pomade, Food Res. Int. 40, 39–46.

[8] Zakaria, J. H., Zaid, M., Hashemi, M. H., Mohideen Batcha, M. F., & Asmuin, N. (2014), Drying of sponge media using swirling fluidized bed dryer, Applied Mechanics and Materials, 660, 644-648