#### **PAPER • OPEN ACCESS**

### Mathematical modelling of paddy drying using fluidized bed dryer

To cite this article: S Suherman and E E Susanto 2019 IOP Conf. Ser.: Mater. Sci. Eng. 543 012010

View the article online for updates and enhancements.



## IOP ebooks<sup>™</sup>

Bringing you innovative digital publishing with leading voices to create your essential collection of books in STEM research.

Start exploring the collection - download the first chapter of every title for free.

# Mathematical modelling of paddy drying using fluidized bed dryer

#### S Suherman<sup>\*</sup> and E E Susanto

Department of Chemical Engineering Faculty of Engineering Diponegoro University Jl Prof H. Soedarto, SH, Tembalang, Semarang, Indonesia 50275

\*Email: suherman.mz@che.undip.ac.id

Abstract. Several mathematical models have been developed to illustrate the drying process of crops, and one of them is thin-layer modelling. However, there are still limited information about mathematical modelling in paddy drying. In this paper, thin layer modelling of paddy drying curve on drying using fluidized bed dryer is presented. The drying paddy was done with drying temperature variations of 50, 60, 70, 80, and 90 °C. The initial paddy moisture content is 33 % dry basis. The drying process was done for 1,5 hours. Paddy moisture was measured every 10 minutes using grain moisture meter. The thin layer models used are Newton, Page, Modified Page, Henderson and Pabis, Logarithmic, Two-term, and Wang and Singh models. Model fittings were done using MATLAB 2015 software by sum square error minimization. Experimental results showed that Modified Page model gave the best results, evidenced by the highest average R<sup>2</sup> value of 0.9949 and lowest average RMSE (Root Mean Square Error) value of 0.0631, followed by Page model and Henderson and Pabis model. The plotting of MR (Moisture Ratio) and time at five drying temperatures showed that effective diffusivity (Deff) value ranged from 1.0334 x 10<sup>-8</sup> m<sup>2</sup>/s to 2.1983 x 10<sup>-8</sup> m<sup>2</sup>/s and the value increases as drying temperature increases. The plotting results of ln Deff and 1/T (absolute temperature) showed that the value of diffusivity factor ( $D_o$ ) is 8.5293 x 10<sup>-6</sup> m<sup>2</sup>/s and activation energy (Ea) is 18.11 kJ/mol.

#### 1. Introduction

Paddy provides around 20 % of total energy per capita and 13 % protein for global population. In Asia, paddy contributes to 35 % energy and 28 % protein, in South America 12 % energy and 9 % protein. Paddy is the main food in several developing countries, contributing to 4000 kJ energy per capita everyday. Starch is the main component of paddy ( $\pm$ 75 %) which located in the endosperm, shaped like granules with the size of 3-10 µm. Protein is the second component in paddy ( $\pm$ 8 %), located inside the endosperm, shaped like particles with the size of 1-4 µm. Harvested paddy usually has moisture content of 20 % or more (wet basis), therefore it has to be dried before being kept in storage. In tropical countries, paddy is usually dried by direct sunlight until it reaches moisture content of 14 % (wet basis). At this condition, paddy can be stored for 2-3 months. If further storage time is needed, the paddy's moisture content must be lowered to 12 % (wet basis) using dryer [1].

Drying is one of the oldest and most commonly used food preserving methods. The most common drying method used until now is by drying directly under the sun (sun drying). However, recently there are lots of improvement and development on mechanical or semi-mechanical drying methods, which are cheap and effective in handling various adversities of sun drying like the need of wide area to dry the material,

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

Published under licence by IOP Publishing Ltd

fluctuation of solar radiation, weather change, contamination of microorganism, animal, and other chemical reactions. One of the artificial drying methods developed is Fluidized Bed Dryer (FBD) [2]. Fluidized Bed Dryer is a good alternative for paddy drying due to uniform product quality due to complete mixing and its high drying capacity due to high ratio of air mass to mass of product [3]. The drying rate of paddy in fluidized bed dryer was affected by drying air temperature and bed thickness [4]. The maximum drying temperature in fluidized bed was suggested as 115 °C to reduce moisture to 24-25% (d.b.) for ensuring rice quality [5]. The drying temperature in pulsed fluidized bed should be less than 145 °C for initial paddy moisture content of 28% (d.b.) to maintain rice quality [6].

Several mathematical models have been developed to illustrate the drying process. One of the modelling method commonly used on agricultural drying is thin layer modelling. There are several researches about thin layer modelling, such as by Jafari et al. (2017) about paddy drying in semi-industrial continuous band microwave dryer, Behera and Sutar (2018) about parboiling of paddy, and Li et al. (2016) about changes in moisture effective diffusivity and glass transition temperature of paddy during drying [7-9]. However, study about modelling of paddy drying in FBD has yet to be found. Therefore, the aim of this study is to determine the paddy drying kinetics on FBD by thin layer models and determine the value of activation energy, effective diffusivity, and its relation with temperature.

#### 2. Experimental methods

#### 2.1. Drying process

This study was performed in the Laboratory of Department of Chemical Engineering, Faculty of Engineering, Diponegoro University. The paddy used in this experiment was taken from Sragen region, Middle Java. 10 grams of paddy was put in a porcelain cup, then placed on 105 °C oven to determine the initial moisture content. The weight of the sample was measured every 10 minutes until it reaches constant value. From this test, paddy initial moisture content of 33 % dry basis was obtained. For drying operation, 200 grams of paddy were used. Paddy was inserted in the fluidization column to be dried for 90 minutes at different temperatures of 50, 60, 70, 80, and 90 °C. Every 10 minutes, a small portion of paddy was taken from the fluidization column to measure its moisture content using grain moisture meter.

#### 2.2. Mathematical modelling

Seven drying models were used in this study. The modelling was done using MATLAB software. The definition of Moisture Ratio (MR) is shown in equation (1)

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

Where M is moisture content at certain time, Mo is initial moisture content, and Me is equilibrium moisture content. To determine the accuracy of the models, there are 2 parameters that can be used, namely Root Mean Square Error (RMSE) and determination coefficient ( $R^2$ ). The calculations of RMSE and  $R^2$  were done using Microsoft Excel. A model is said to be suitable if it has high  $R^2$  value and low RMSE value. The calculations of RMSE and  $R^2$  are expressed in equation (2) and (3) [10].

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (MR_{exp,i} - MR_{pre,i})^2}$$
(2)

$$R^{2} = \frac{\left[\sum_{i=1}^{N} (MR_{exp,i},\overline{MR_{exp}})(MR_{pre,i},\overline{MR_{pre}})\right]^{2}}{\sum_{i=1}^{N} (MR_{exp,i},\overline{MR_{pre}})^{2} \sum_{i=1}^{N} (MR_{pre,i},\overline{MR_{pre}})^{2}}$$
(3)

Where  $Mr_{exp}$  is experimental Moisture Ratio,  $Mr_{pre}$  is Predicted Moisture Ratio, and N is number of observations.

#### 2.3. Effective diffusivity and activation energy

Drying characteristics on falling rate period can be determined using Fick's diffusion equation. With the assumptions of spherical paddy coordinate, uniform initial moisture content distribution, and long drying time, the relation of Moisture Ratio and Effective Diffusivity can be expressed with equation (4) [8]:

$$MR = \frac{6}{\pi^2} \exp\left[\frac{-Deff \pi^2}{r^2} \theta\right]$$
(4)

Where  $D_{eff}$  is effective diffusivity (m<sup>2</sup>/s), r is the radius of paddy (m),  $\theta$  is drying time (s), dan  $\pi$  is a constant. By changing equation (4) into logarithmic form, a new linear equation is obtained, as shown in equation (5).

$$\ln MR = \ln \left[\frac{6}{\pi^2}\right] - \frac{\text{Deff }\pi^2}{r^2} \theta$$
(5)

The value of effective diffusivity ( $D_{eff}$ ) can be determined by plotting the ln MR data versus drying time ( $\theta$ ). From the slope value obtained, effective diffusivity can be calculated. Furthermore, the relation of effective diffusivity and drying temperature can be illustrated with Arrhenius equation, as shown in equation (6) [11].

$$\mathbf{D}_{\rm eff} = \mathbf{D}_{\rm o} \exp\left[-\frac{\mathbf{E}a}{\mathbf{R}T}\right] \tag{6}$$

Where  $D_o$  is diffusivity constant at infinite drying temperature (m<sup>2</sup>/s), R is universal gas constant (8.314 J/mol.K), Ea is activation energy (kJ/mol), and T is absolute temperature (K). The value of Ea and  $D_o$  can be determined by plotting ln  $D_{eff}$  and 1/T, after linearization of the equation above, as shown in equation (7).

$$\ln D_{\rm eff} = \ln D_{\rm o} - \frac{E_{\rm a}}{R_{\rm T}}$$
(7)

#### 3. Results and discussion

#### 3.1. Drying curve analysis

The relation of Moisture Ratio and drying time at five different drying temperatures is shown in Figure 1. From Figure 1, it is shown that as drying time increases, the Moisture Ratio decreases, and the higher the drying temperature, the reduction of Moisture Ratio become bigger. As a comparison, on research performed by Kamin and Janaun (2017) about paddy drying in a Laterally Aerated Moving Bed Dryer, at ambient temperature, it took 5 hours to reduce paddy's moisture ratio from 1 to approximately 0,72 [12]. It can be concluded that the whole process of paddy drying were happened on falling rate period and the most important factor that affects paddy drying is moisture diffusion.



Figure 1. Drying curve of paddy using Fludized Bed Dryer at different temperatures

#### 3.2. Modelling results

]

(

Seven models of thin layer drying were fitted with experimental Moisture Ratio data at five different temperatures. The models used are shown in table 1. The model with highest  $R^2$  value and lowest RMSE value is considered the most suitable model to illustrate paddy drying kinetics on FBD. Modelling results shown that the most suitable model is Modified Page model, followed by Page model and Henderson and Pabis Model. The value of model constants used and the value of  $R^2$  and RMSE are shown in table 2 while figure 2 shows the comparison of drying curve between experimental results and modelling results, in this case Modified Page model was used. From figure 2, it can be observed that there is a good agreement between experimental results and Modified Page model.

Table 1. Thin layer drying models					
No	Model	Formula	References		
1	Newton	MR = exp(-kt)	Ayensu [13]		
2	Page	$MR = exp(-kt^n)$	Menges and Ertekin [14]		
3	Modified Page	$MR = \exp(-kt)^n$	White et al. [15]		
1	Henderson and Pabis	$MR = a \exp(-kt)$	Kashaninejad et al. [16]		
5	Logarithmic	$MR = a \exp(-kt) + c$	Togrul dan Pehlivan [17]		
5	Two-term	$MR = a \exp(-k_1 t) + b \exp(-k_2 t)$	Wang et al. [18]		
7	Wang and Singh	$MR = 1 + at + bt^2$	Wang et al. [18]		



Figure 2. Drying curve comparison between experimental results and prediction results of Modified Page model

IOP Conf. Series: Materials Science and Engineering 543 (2019) 012010 doi:10.1088/1757-899X/543/1/012010

Newton         50         0.0083         0.9898         0.0750           60         0.0109         0.9784         0.1227           70         0.0144         0.9700         0.1630           80         0.0235         0.9687         0.1803           90         0.0235         0.9759         0.1712           90         0.0235         0.9980         0.0300           60         0.0266         0.7709         0.9980         0.0300           70         0.0286         0.8241         0.9980         0.0300           70         0.0266         0.7709         0.9984         0.1208           90         0.0308         0.9277         0.9984         0.1345           Modified Page         50         0.0062         0.7499         0.9984         0.119           60         0.0086         0.711         0.9982         0.0158           80         0.012         0.6694         0.9970         0.0454           90         0.0237         0.5007         0.9811         0.1227           Henderson and         50         0.0095         0.9489         0.9735         0.0363           90         0.0132         0.8451	Model	T ( <sup>0</sup> C)	k	n	а	b	с	$\mathbf{k}_1$	$k_2$	$\mathbb{R}^2$	RMSE
60       0.0109       0.1227         70       0.0144       0.9784       0.1227         90       0.0235       0.9687       0.1803         90       0.02269       0.7709       0.9759       0.1712         90       0.02269       0.7709       0.9980       0.0300         70       0.0286       0.8241       0.9980       0.0300         70       0.0286       0.8241       0.9980       0.0300         70       0.0286       0.8241       0.9980       0.0300         70       0.0286       0.8241       0.9980       0.1208         90       0.0308       0.9277       0.9840       0.1345         90       0.0308       0.9277       0.9984       0.1119         90       0.0237       0.7978       0.9984       0.1119         90       0.0207       0.6694       0.9990       0.0184         90       0.0163       0.9633       9.9970       0.0454         90       0.0163       0.9633       9.9970       0.0454         90       0.0163       0.9633       9.9970       0.0454         90       0.0163       0.9633       9.9171       0.0859     <	Newton	50	0.0083							0.9898	0.0750
700.01440.01630.06370.1630800.01330.06870.1803900.02350.96870.1803600.02690.7090.99800.0300700.02680.82410.999800.0300700.02860.82410.999800.0300900.03080.92770.999800.9818900.03080.92770.999800.9814900.03080.92770.999800.1208900.03080.92770.999800.1345900.02120.66940.999900.0156900.01230.59780.999800.0198800.01330.95780.99700.0454900.01530.94890.99700.0454900.01550.78780.99730.0973900.01550.78780.94710.0859900.01550.78780.94710.0859900.01550.78780.94710.0859900.01550.78780.94710.03631000.01240.77720.11130.94510.9459900.01550.78780.94710.0363900.01550.78780.94710.0662900.01670.81540.11370.94510.9459900.01550.78780.94710.96620.0662910.01630.78780.11370.94510.9451		60	0.0109							0.9784	0.1227
80         0.0183         0.9687         0.1803           90         0.0235         0.9759         0.1712           90         0.0272         0.6985         0.9960         0.0300           70         0.0286         0.8241         0.9980         0.0308           70         0.0286         0.821         0.9980         0.0308           70         0.0286         0.821         0.9980         0.0308           70         0.0280         0.8785         0.9980         0.0308           70         0.0203         0.8785         0.9980         0.0308           70         0.012         0.6994         0.9990         0.1345           70         0.012         0.6997         0.9990         0.0198           80         0.012         0.6997         0.9990         0.0198           90         0.0133         0.5978         9.9970         0.0454           90         0.0132         0.9633         0.9973         0.0393           Pabis         9.9970         0.0145         0.9984         0.9973         0.0373           103         0.0132         0.8451         0.1137         0.9971         0.0859 <td< td=""><td></td><td>70</td><td>0.0144</td><td></td><td></td><td></td><td></td><td></td><td></td><td>0.9700</td><td>0.1630</td></td<>		70	0.0144							0.9700	0.1630
90         0.0235         0.9759         0.1712           Page         50         0.0272         0.6985         0.9960         0.0408           60         0.0269         0.8241         9.9980         0.0300           70         0.0286         0.8241         9.9980         0.0300           80         0.0293         0.8785         9.9984         0.1208           90         0.0308         0.9277         9.9984         0.1208           90         0.0308         0.9277         9.9984         0.1345           Modified Page         50         0.0062         0.749         9.9992         0.0156           70         0.012         0.6694         9.9990         0.0184         9.9990         0.0184           80         0.0163         0.5978         9.9970         0.0454           90         0.0237         0.5007         9.9970         0.0454           90         0.0163         0.9082         9.9970         0.0454           90         0.0155         0.7878         9.911         0.0363           90         0.0155         0.7878         9.911         0.0363           100363         0.0115         0.9459		80	0.0183							0.9687	0.1803
Page         50         0.0272         0.6985         0.9960         0.0408           60         0.0269         0.7709         0.9980         0.0300           70         0.0286         0.8241         0.9980         0.0300           80         0.0293         0.8785         0.9984         0.1208           90         0.0308         0.9277         0.9843         0.1208           90         0.0062         0.7499         0.9984         0.119           60         0.0062         0.7499         0.9992         0.0156           70         0.012         0.6694         9.9990         0.0198           80         0.0163         0.5978         9.9970         0.0454           90         0.0237         0.5007         9.9970         0.0454           90         0.0135         0.9633         9.9970         0.0454           Pabis         9.9970         0.0454         9.9970         0.0454           10         0.0116         0.9082         9.9585         0.0867           10         0.0116         0.9082         9.9585         0.9585         0.9585           10         0.0116         0.9082         9.9597		90	0.0235							0.9759	0.1712
60       0.0269       0.7709       0.9980       0.0300         70       0.0286       0.8241       0.9983       0.0918         80       0.0293       0.8785       0.9843       0.1208         90       0.0308       0.9277       0.9843       0.1345         Modified Page       50       0.0062       0.7499       0.9992       0.0156         60       0.0086       0.711       0.9990       0.0198         80       0.0163       0.5978       0.9990       0.0198         90       0.0237       0.507       0.9843       0.1227         Henderson and       50       0.0073       0.9463       0.9970       0.0454         70       0.0116       0.9082       0.9373       0.0303         Pabis       0       0.0132       0.8451       0.9471       0.0859         90       0.0155       0.7878       0.9459       0.9772       0.9459       0.9772         Logarithmic       50       0.0089       0.8598       0.1137       0.9961       0.0624         90       0.0201       0.8154       0.1139       0.9662       0.0624         90       0.0201       0.8796       0.1115	Page	50	0.0272	0.6985						0.9960	0.0408
70         0.0286         0.8241         0.9908         0.0918           80         0.0293         0.8785         0.9843         0.1208           90         0.0308         0.9277         0.9984         0.1119           60         0.0086         0.711         0.9994         0.1119           60         0.0086         0.711         0.9990         0.0198           70         0.012         0.6694         0.9990         0.0198           80         0.0163         0.5978         0.9970         0.0454           90         0.0237         0.5007         0.9873         0.0393           Pabis         0         0.016         0.9483         0.1227           Henderson and         50         0.0073         0.9633         0.9873         0.0393           Pabis         0         0.0155         0.7878         0.9735         0.0734           10         0.0116         0.9082         0.9459         0.0972           Logarithmic         50         0.0089         0.8598         0.1137         0.9911         0.0363           10         0.0134         0.7772         0.1114         0.9662         0.0624           10		60	0.0269	0.7709						0.9980	0.0300
80         0.0293         0.8785         0.9843         0.1208           90         0.0308         0.9277         0.9840         0.1345           Modified Page         50         0.0062         0.7499         0.9992         0.0156           70         0.012         0.6694         0.9990         0.0198           80         0.0137         0.9778         0.9970         0.0454           90         0.0237         0.5007         0.9970         0.0454           90         0.0237         0.9633         0.9873         0.0393           Pabis         0.0016         0.9982         0.9735         0.0734           70         0.0116         0.9082         0.9585         0.0867           90         0.0155         0.7878         0.9459         0.9972           Logarithmic         50         0.0089         0.8598         0.1137         0.9911         0.0363           60         0.0164         0.7772         0.114         0.9662         0.0624           70         0.0134         0.7772         0.114         0.9663         0.0042           70         0.021         0.6901         0.1045         0.9663         0.0042		70	0.0286	0.8241						0.9908	0.0818
90         0.0308         0.9277         0.9840         0.1345           Modified Page         50         0.0062         0.7499         0.9992         0.0156           70         0.012         0.6694         0.9990         0.0198           80         0.0163         0.5978         0.9970         0.0454           90         0.0237         0.5007         0.9811         0.1227           Henderson and         50         0.0073         0.9633         0.9735         0.0973           Pabis         0         0.0165         0.9489         0.9735         0.0734           60         0.0095         0.9489         0.9471         0.0859           90         0.0155         0.7878         0.9451         0.9911           Logarithmic         50         0.0089         0.8598         0.1137         0.9911         0.0363           60         0.0171         0.8154         0.1139         0.9911         0.0363           100         0.0161         0.7258         0.1105         0.9662         0.0624           100         0.0161         0.7258         0.1015         0.9603         0.0755           100         0.0201         0.6766		80	0.0293	0.8785						0.9843	0.1208
Modified Page         50         0.0062         0.7499         0.1119           60         0.0086         0.711         0.9992         0.0156           70         0.012         0.6694         0.9990         0.0188           80         0.0163         0.5978         0.9970         0.0454           90         0.0237         0.5007         0.9811         0.1227           Henderson and         50         0.0073         0.9633         0.9873         0.0973           Pabis         0         0.0116         0.9082         0.9735         0.0734           70         0.0112         0.8481         0.1137         0.9459         0.0972           Logarithmic         0         0.0155         0.7878         0.9459         0.0911         0.0363           60         0.0107         0.8154         0.1137         0.9911         0.0363           70         0.0134         0.7772         0.1114         0.9662         0.0624           80         0.0161         0.7258         0.1007         0.9810         0.1066           70         0.0201         0.6901         0.1045         0.9963         0.0755           90         0.0201		90	0.0308	0.9277						0.9840	0.1345
60       0.0086       0.711       0.9992       0.0156         70       0.012       0.6694       0.9990       0.0198         80       0.0163       0.5978       0.9970       0.0454         90       0.0073       0.9633       0.9811       0.1227         Henderson and       0       0.0075       0.9633       0.9735       0.0734         Pabis       0       0.0116       0.9082       0.9735       0.0734         70       0.0116       0.9082       0.9489       0.9471       0.0859         90       0.0155       0.7878       0.9471       0.0859         90       0.0161       0.772       0.1137       0.9911       0.0363         Logarithmic       50       0.0091       0.1137       0.9911       0.0363         60       0.0107       0.8154       0.1139       0.9778       0.0483         70       0.0134       0.7772       0.1114       0.9662       0.0624         80       0.0161       0.7258       0.1055       0.0979       0.0221       0.9939       0.9960         7wo-term       50       0.8376       0.1155       0.0079       0.0221       0.9939       0.9960	Modified Page	50	0.0062	0.7499						0.9984	0.1119
70       0.012       0.6694       0.9990       0.0198         80       0.0163       0.5978       0.9970       0.0454         90       0.0237       0.5007       0.9811       0.1227         Henderson and       00       0.0073       0.9633       0.9811       0.1227         Pabis       0       0.0095       0.9489       0.9735       0.0734         70       0.0116       0.9082       0.9489       0.9487       0.0859         90       0.0155       0.7878       0.9471       0.0859         90       0.0155       0.7878       0.9471       0.0633         Logarithmic       50       0.009       0.8598       0.1137       0.9911       0.0363         60       0.0107       0.8154       0.1139       0.9778       0.0483         70       0.0134       0.7772       0.1114       0.9662       0.0624         80       0.0161       0.7258       0.1025       0.9939       0.9960         70       0.0201       0.6901       0.1045       0.9662       0.0624         70       0.221       0.9939       0.0960       0.1110       0.9662       0.0975         80 <t< td=""><td></td><td>60</td><td>0.0086</td><td>0.711</td><td></td><td></td><td></td><td></td><td></td><td>0.9992</td><td>0.0156</td></t<>		60	0.0086	0.711						0.9992	0.0156
80         0.0163         0.5978         0.9970         0.0454           90         0.0237         0.5007         0.9813         0.1227           Henderson and Pabis         50         0.0073         0.9633         0.9873         0.0393           Pabis         60         0.0095         0.9489         0.9735         0.0734           60         0.0016         0.9082         0.9735         0.0734           70         0.0155         0.8451         0.9471         0.0859           90         0.0155         0.7878         0.9110         0.0363           100         0.0107         0.8154         0.1137         0.9911         0.0363           100         0.0107         0.8154         0.1139         0.9778         0.0483           100         0.0134         0.7772         0.1114         0.9662         0.0624           100         0.0201         0.6901         0.1045         0.9651         0.0942           Two-term         50         0.0201         0.6901         0.1045         0.9662         0.0971           100         0.9125         0.1152         0.0079         0.0221         0.9939         0.0960           100		70	0.012	0.6694						0.9990	0.0198
90         0.0237         0.5007         0.9811         0.1227           Henderson and Pabis         50         0.0073         0.9633         0.9873         0.0393           Pabis         60         0.0095         0.9489         0.9735         0.0734           60         0.0016         0.9082         0.9585         0.0857           80         0.0132         0.8451         0.9459         0.9972           Logarithmic         60         0.0107         0.8154         0.1137         0.9911         0.0363           60         0.0107         0.8154         0.1139         0.9778         0.0483           70         0.0114         0.7772         0.1114         0.9662         0.0624           80         0.0161         0.7258         0.1105         0.9651         0.0942           70         0.0201         0.6901         0.1045         0.9651         0.0942           Two-term         50         0.0201         0.6901         0.1045         0.9810         0.1066           70         0.221         0.9919         0.0960         0.1110         0.9622         0.9977           80         0.7839         0.1112         0.0141         0.021		80	0.0163	0.5978						0.9970	0.0454
Henderson and Pabis         50         0.0073         0.9633         0.0873         0.0393           Pabis         60         0.0095         0.9489         0.9735         0.0734           70         0.0116         0.9082         0.9585         0.0867           80         0.0132         0.8451         0.9489         0.9459         0.0972           Logarithmic         50         0.0089         0.8598         0.1137         0.9911         0.0363           60         0.0107         0.8154         0.1139         0.9778         0.0483           70         0.0134         0.7772         0.1114         0.9662         0.0624           80         0.0161         0.7258         0.1005         0.9939         0.0960           70         0.0201         0.6901         0.1045         0.9663         0.0755           90         0.0201         0.6901         0.1045         0.9663         0.0755           90         0.0201         0.6901         0.1045         0.9939         0.9060           60         0.7334         0.1155         0.007         0.0221         0.9810         0.1066           70         0.8331         0.1151         0.012 </td <td></td> <td>90</td> <td>0.0237</td> <td>0.5007</td> <td></td> <td></td> <td></td> <td></td> <td></td> <td>0.9811</td> <td>0.1227</td>		90	0.0237	0.5007						0.9811	0.1227
60         0.0095         0.9489         0.9735         0.0734           70         0.0116         0.9082         0.9585         0.0867           80         0.0132         0.8451         0.9471         0.0859           90         0.0155         0.7878         0.9459         0.0972           Logarithmic         50         0.0089         0.8598         0.1137         0.9911         0.0363           60         0.0107         0.8154         0.1139         0.9778         0.0483           70         0.0134         0.7772         0.1114         0.9662         0.0624           80         0.0161         0.7258         0.1105         0.9603         0.0755           90         0.0201         0.6901         0.1045         0.9662         0.0624           80         0.0161         0.7258         0.1105         0.9603         0.0755           90         0.0201         0.6901         0.1045         0.9662         0.0942           Two-term         50         0.9125         0.1155         0.0079         0.0221         0.9810         0.1066           70         0.8331         0.1151         0.012         0.211         0.9660	Henderson and Pabis	50	0.0073		0.9633					0.9873	0.0393
70         0.0116         0.9082         0.9585         0.0867           80         0.0132         0.8451         0.9471         0.0859           90         0.0155         0.7878         0.9911         0.0363           60         0.0107         0.8154         0.1139         0.9778         0.0483           70         0.0134         0.7772         0.1114         0.9662         0.0624           80         0.0161         0.7258         0.1105         0.9651         0.0942           70         0.0201         0.6901         0.1045         0.9651         0.0942           70         0.0201         0.6901         0.1045         0.9651         0.0942           70         0.0201         0.6901         0.1045         0.9939         0.0960           60         0.0201         0.6901         0.1045         0.9939         0.0960           70         0.8331         0.1155         0.0079         0.0221         0.9939         0.0960           70         0.8331         0.1151         0.012         0.911         0.9660         0.1110           80         0.7341         0.1099         0.0121         0.9562         0.0997		60	0.0095		0.9489					0.9735	0.0734
80         0.0132         0.8451         0.9471         0.0859           Logarithmic         50         0.0089         0.8598         0.1137         0.9911         0.0363           60         0.0107         0.8154         0.1139         0.9778         0.0483           70         0.0134         0.7772         0.1114         0.9662         0.0624           80         0.0161         0.7258         0.1105         0.9651         0.0942           70         0.0201         0.6901         0.1045         0.9913         0.0960           70         0.0201         0.6901         0.1045         0.9651         0.0942           70         0.0201         0.6901         0.1045         0.9651         0.0942           70         0.0201         0.6901         0.1045         0.9651         0.0942           70         0.9125         0.1155         0.0079         0.022         0.9810         0.1066           70         0.8331         0.1151         0.012         0.911         0.9660         0.1110           80         0.7341         0.1099         0.0172         0.0207         0.9557         0.0870           90         0.7341         <		70	0.0116		0.9082					0.9585	0.0867
90         0.0155         0.7878         0.9459         0.0972           Logarithmic         50         0.0089         0.8598         0.1137         0.9911         0.0363           60         0.0107         0.8154         0.1139         0.9778         0.0483           70         0.0134         0.7772         0.1114         0.9662         0.0624           80         0.0161         0.7258         0.1105         0.9651         0.0942           Two-term         50         0.0201         0.6901         0.1045         0.9939         0.0960           60         0.0201         0.6901         0.1045         0.9939         0.0960           60         0.8766         0.1155         0.0079         0.0221         0.9939         0.0960           70         0.8331         0.1151         0.012         0.9111         0.9660         0.1110           80         0.7839         0.112         0.0141         0.0214         0.9562         0.0997           90         0.7341         0.1099         0.0172         0.0207         0.9557         0.0870           90         0.061         -0.0002         0.5413         0.8455         0.3922         1.6431 <td></td> <td>80</td> <td>0.0132</td> <td></td> <td>0.8451</td> <td></td> <td></td> <td></td> <td></td> <td>0.9471</td> <td>0.0859</td>		80	0.0132		0.8451					0.9471	0.0859
Logarithmic         50         0.0089         0.8598         0.1137         0.9911         0.0363           60         0.0107         0.8154         0.1139         0.9778         0.0483           70         0.0134         0.7772         0.1114         0.9662         0.0624           80         0.0161         0.7258         0.1105         0.9651         0.0942           90         0.0201         0.6901         0.1045         0.9651         0.0960           60         0.8766         0.1152         0.0079         0.0221         0.9939         0.0960           60         0.8766         0.1155         0.0097         0.022         0.9810         0.1066           70         0.8331         0.1151         0.012         0.0211         0.9660         0.1110           80         0.7839         0.1112         0.0141         0.0214         0.9562         0.0997           90         0.7341         0.1099         0.0172         0.207         0.9557         0.870           90         0.0061         -0.0002         0.5413         0.8455         0.0062         0.0003         0.5413         0.8455           70         0.0062         -0.0003		90	0.0155		0.7878					0.9459	0.0972
60         0.0107         0.8154         0.1139         0.9778         0.0483           70         0.0134         0.7772         0.1114         0.9662         0.0624           80         0.0161         0.7258         0.1105         0.9603         0.0755           90         0.0201         0.6901         0.1045         0.9651         0.0942           Two-term         50         0.9125         0.1152         0.0079         0.0221         0.9939         0.0960           60         0.8766         0.1155         0.0097         0.022         0.9810         0.1066           70         0.8331         0.1151         0.012         0.0211         0.9660         0.1110           80         0.7839         0.1112         0.0141         0.0214         0.9562         0.0997           90         0.7341         0.1099         0.0172         0.0207         0.9557         0.0870           Wang and Singh         50         0.0062         -0.0002         0.6783         0.8202           60         0.0061         -0.0002         0.5413         0.8455           70         0.0062         -0.0003         0.5413         0.8455           70	Logarithmic	50	0.0089		0.8598		0.1137			0.9911	0.0363
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	-	60	0.0107		0.8154		0.1139			0.9778	0.0483
80         0.0161         0.7258         0.1105         0.9603         0.0755           90         0.0201         0.6901         0.1045         0.9651         0.0942           Two-term         50         0.9125         0.1152         0.0079         0.0221         0.9939         0.0960           60         0.8766         0.1155         0.0097         0.022         0.9810         0.1066           70         0.8331         0.1151         0.012         0.0211         0.9662         0.0997           80         0.7839         0.1112         0.0141         0.0214         0.9562         0.0997           90         0.7341         0.1099         0.0172         0.0207         0.9557         0.0870           Wang and Singh         50         0.0062         -0.0002         0.5413         0.8455           70         0.0062         -0.0003         0.5413         0.8455           70         0.0062         -0.0003         0.5116         1.5674           90         0.0061         -0.0003         0.5490         1.5393		70	0.0134		0.7772		0.1114			0.9662	0.0624
90         0.0201         0.6901         0.1045         0.9651         0.0942           Two-term         50         0.9125         0.1152         0.0079         0.0221         0.9939         0.0960           60         0.8766         0.1155         0.0097         0.022         0.9810         0.1066           70         0.8331         0.1151         0.012         0.0211         0.9660         0.1110           80         0.7839         0.1112         0.0141         0.0214         0.9562         0.0997           90         0.7341         0.1099         0.0172         0.0207         0.9557         0.0870           Wang and Singh         50         0.0062         -0.0002         0.6783         0.8202           60         0.0061         -0.0002         0.5413         0.8455           70         0.0062         -0.0003         0.5116         1.5674           90         0.0061         -0.0003         0.5490         1.5393		80	0.0161		0.7258		0.1105			0.9603	0.0755
Two-term         50         0.9125         0.1152         0.0079         0.0221         0.9939         0.0960           60         0.8766         0.1155         0.0097         0.022         0.9810         0.1066           70         0.8331         0.1151         0.012         0.0211         0.9660         0.1110           80         0.7839         0.1112         0.0141         0.0214         0.9562         0.0997           90         0.7341         0.1099         0.0172         0.0207         0.9557         0.0870           Wang and Singh         50         0.0062         -0.0002         0.6783         0.8202           60         0.0061         -0.0002         0.5413         0.8455           70         0.0062         -0.0003         0.5116         1.5674           90         0.0061         -0.0003         0.5490         1.5393		90	0.0201		0.6901		0.1045			0.9651	0.0942
60         0.8766         0.1155         0.0097         0.022         0.9810         0.1066           70         0.8331         0.1151         0.012         0.0211         0.9660         0.1110           80         0.7839         0.1112         0.0141         0.0214         0.9562         0.0997           90         0.7341         0.1099         0.0172         0.0207         0.9557         0.0870           Wang and Singh         50         0.0062         -0.0002         0.5413         0.8455           60         0.0062         -0.0003         0.3922         1.6431           80         0.0063         -0.0003         0.5116         1.5674           90         0.0061         -0.0003         0.5490         1.5393	Two-term	50			0.9125	0.1152		0.0079	0.0221	0.9939	0.0960
70         0.8331         0.1151         0.012         0.0211         0.9660         0.1110           80         0.7839         0.1112         0.0141         0.0214         0.9562         0.0997           90         0.7341         0.1099         0.0172         0.0207         0.9557         0.0870           Wang and Singh         50         0.0062         -0.0002         0.6783         0.8202           60         0.0061         -0.0002         0.5413         0.8455           70         0.0062         -0.0003         0.3922         1.6431           80         0.0063         -0.0003         0.5116         1.5674           90         0.0061         -0.0003         0.5490         1.5393		60			0.8766	0.1155		0.0097	0.022	0.9810	0.1066
80         0.7839         0.1112         0.0141         0.0214         0.9562         0.0997           90         0.7341         0.1099         0.0172         0.0207         0.9557         0.0870           Wang and Singh         50         0.0062         -0.0002         0.6783         0.8202           60         0.0061         -0.0002         0.5413         0.8455           70         0.0063         -0.0003         0.5116         1.5674           90         0.0061         -0.0003         0.5490         1.5393		70			0.8331	0.1151		0.012	0.0211	0.9660	0.1110
90         0.7341         0.1099         0.0172         0.0207         0.9557         0.0870           Wang and Singh         50         0.0062         -0.0002         0.6783         0.8202           60         0.0061         -0.0002         0.5413         0.8455           70         0.0062         -0.0003         0.3922         1.6431           80         0.0063         -0.0003         0.5116         1.5674           90         0.0061         -0.0003         0.5490         1.5393		80			0.7839	0.1112		0.0141	0.0214	0.9562	0.0997
Wang and Singh         50         0.0062         -0.0002         0.6783         0.8202           60         0.0061         -0.0002         0.5413         0.8455           70         0.0062         -0.0003         0.3922         1.6431           80         0.0063         -0.0003         0.5116         1.5674           90         0.0061         -0.0003         0.5490         1.5393		90			0.7341	0.1099		0.0172	0.0207	0.9557	0.0870
600.0061-0.00020.54130.8455700.0062-0.00030.39221.6431800.0063-0.00030.51161.5674900.0061-0.00030.54901.5393	Wang and Singh	50			0.0062	-0.0002				0.6783	0.8202
700.0062-0.00030.39221.6431800.0063-0.00030.51161.5674900.0061-0.00030.54901.5393		60			0.0061	-0.0002				0.5413	0.8455
800.0063 -0.00030.51161.5674900.0061 -0.00030.54901.5393		70			0.0062	-0.0003				0.3922	1.6431
90 0.0061 -0.0003 0.5490 1.5393		80			0.0063	-0.0003				0.5116	1.5674
		90			0.0061	-0.0003				0.5490	1.5393

Table 2. Thin layer modelling results and value of constants used on paddy drying using FBD

3.3. The effective diffusivity and activation energy in paddy drying using FBD

The effective diffusivity of paddy on drying using FBD at five different temperatures can be determined by plotting ln MR vs time, as shown in figure 3. Table 3 shows paddy's effective diffusivity at different temperatures. From Table 3, it can be observed that the value of effective diffusivity increases as drying temperature increases. Therefore, it can be implied that high temperature will cause water inside the paddy to diffuse to drying air because of the difference in temperature and pressure between drying air and paddy [19]. As a comparison, effective diffusion determination with the same Fick's law on the drying of macroalgae (*Oedogonium sp.*) using solar drying performed by Hammond et al. (2018) shows that, at the drying temperature of 25-60 °C, the optimum effective diffusivity of macroalgae obtained was 5.67 x  $10^{-9}$  m<sup>2</sup>/s [20].

**IOP** Publishing

IOP Conf. Series: Materials Science and Engineering 543 (2019) 012010 doi:10.1088/1757-899X/543/1/012010



Figure 3. Plotting of ln MR versus drying time

Table 3. Effective diffusivity of paddy dried at different temperatures

No	Temperature ( <sup>0</sup> C)	Effective Diffusivity (m <sup>2</sup> /s)
1	50	1.033 x 10 <sup>-8</sup>
2	60	1.214 x 10 <sup>-8</sup>
3	70	1.439 x 10 <sup>-8</sup>
4	80	1.732 x 10 <sup>-8</sup>
5	90	2.198 x 10 <sup>-8</sup>

Figure 4 shows the relation of effective diffusivity (ln  $D_{eff}$ ) and absolute temperature. From Figure 4 it can be implied that the relation of effective diffusivity and absolute temperature is linear, which relates to Arrhenius relation between diffusivity coefficient and temperature [19]. According to Figure 4, the R<sup>2</sup> value (determination coefficient) is 0.9872. From the plotting results, the value of diffusivity constant ( $D_o$ ) obtained is 8.529 x 10<sup>-6</sup> m<sup>2</sup>/s and the value of activation energy (Ea) obtained is 18.11 kJ/mol.



Figure 4. Plotting of ln D<sub>eff</sub> versus 1/T

#### 4. Conclusions

Modified Page model is the most suitable model to illustrate the kinetics of paddy drying using Fluidized Bed Dryer (FBD). The value of effective diffusivity ranges from 1.033 x  $10^{-8}$  to 2.198 x  $10^{-8}$  m<sup>2</sup>/s and will increase as drying temperature increases. The moisture diffusivity of paddy greatly depends on temperature, which follows the Arrhenius relation. From the plotting results of ln D<sub>eff</sub> and 1/T, the value of diffusivity constant (D<sub>o</sub>) obtained is 8.529 x  $10^{-6}$  m<sup>2</sup>/s and the value of activation energy (Ea) obtained is 18.11 kJ/mol.

#### 5. Acknowledgement

The authors want to give thanks to Diponegoro University for funding this research in the program Research of International Publication 2018.

#### References

- [1] Prabowo 2006 Processing and Its Effect on Physico-chemical Properties and Quality of Rice (Theses, Samarinda: Mulawarman University)
- [2] Khalil M S, Salem A Z M, Hassan A A, Gado H M, Alsersy H and Simbaya J 2012 Effects of Sun-Drying and Exogenous Enzymes on Nutrients Intake, Digestibility and Nitrogen Utilization in Sheep Fed Atriplex Halimus Foliages *Anim. Feed Sci. Tech.* **171** 128-35
- [3] Soponronnarit S, Prachayawarakorn S and Wangji M 1996 Commercial Fluidized Bed Paddy Dryer *Proc 10<sup>th</sup> Int Drying Symp, Vol. (A), Krakow, 30 July 2 August, Poland* 638-44
- [4] Tumambing J A and Driscoll R H 1991 Modeling the performance of continuous fluidized bed paddy dryer for rapid pre-drying of paddy Proc 14<sup>th</sup> ASEAN Seminar on Grain Post-harvest Tech. 193-213
- [5] Soponronnarit S and Prachayawarakorn S 1994 Optimum Strategy For Fluidized Bed Paddy Drying *Dry. Technol.* **12** 1667-86
- [6] Prachayawarakorn S, Tia W, Poopaiboon K and Soponronnarit S 2005 Comparison of performances of pulsed and conventional fluidized-bed dryers *J. Stored Prod. Res.* **41** 479-97
- [7] Jafari H, Kalantari D and Azadbakht M 2017 Semi-Industrial Continuous Band Microwave Dryer For Energy and Exergy Analyses, Mathematical Modeling of Paddy Drying and It's Qualitative Study *Energy* 138 1016-29
- [8] Behera G and Sutar P P 2018 A Comprehensive Review of Mathematical Modeling of Paddy Parboiling and Drying: Effects of Modern Techniques on Process Kinetics and Rice Quality *Trends Food Sci. Technol.* 75 206-30
- [9] Li X J, Wang X, Li Y, Jiang P and Lu H 2016 Changes in Moisture Effective Diffusivity and Glass Transition Temperature of Paddy During Drying *Comput. Electron AGR* **128** 112-19
- [10] Dhanushkodi S, Wilson V H and Sudhakar K 2017 Mathematical Modeling of Drying Behavior of Cashew in A Solar Biomass Hybrid Dryer *Resource-Efficient Technol.* 3 359-64
- [11] Shen F, Peng L, Zhang Y, Wu J, Zhang X, Yang G, Peng H, Qi H and Deng S 2011 Thin-Layer Drying Kinetics and Quality Changes of Sweet Sorghum Stalk For Ethanol Production As Affected By Drying Temperature Ind. Crop Prod. 34 1588-94
- [12] Kamin N H and Janaun J 2017 Drying of Paddy in A Laterally Aerated Moving Bed Dryer at Ambient Temperature *Chem. Eng. Trans.* **56** 877-82
- [13] Ayensu A 1997 Dehydration of Food Crops Using A Solar Dryer With Convective Heat Flow Sol Energy 59 pp 121-6
- [14] Menges H and Ertekin O C 2006 Mathematical Modeling of Thin Layer Drying of Golden Apples J. Food Eng. 77 119-25
- [15] White G M, Ross I J and Ponelert R 1981 Fully Exposed Drying of Popcorn Trans ASAE 24 466-68
- [16] Kashaninejad M, Mortazavi A, Safekordi A and Tabil L G 2007 Thin-Layer Drying Characteristics and Modeling of Pistachio Nuts J. Food Eng. **78** 98-108
- [17] Togrul I T and Pehlivan D 2002 Mathematical Modeling of Solar Drying of Apricots in Thin

Layers J. Food Eng. 55 209-16

- [18] Wang Z, Sun J, Liao X, Chen F, Zhao G, Wu J and Hu X 2007 Mathematical Modeling on Hot Air Drying of Thin Layer Apple Pomace *Food Res. Int.* **40** 39-46
- [19] Suherman, Fajar B, Satriadi H, Yuariski O, Nugroho R S and Shobib A 2012 Thin Layer Drying Kinetics of Roselle *Adv. J Food Sci. Technol.* **4** 51-55
- [20] Hammond L, Bai L, Sheehan M and Walker C 2018 Experimental Analysis and Diffusion Modelling of Solar Drying of Macro Algae-Oedogonium sp. *Chem. Eng. Trans.* **65** 427-32