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Drying Kinetic Models of Rice Applying Fluidized Bed Dryer

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ABSTRACT

Rice is the main food in Indonesia. Rice drying by using the traditional method directly under the sun light can require a long time to complete. The aim of this study is to investigate the appropriate kinetics modeling of rice with applied by fluidized bed dryer. A rice bed with 2-cm thickness has been dried at various temperatures (50°C, 60°C, and 70°C) with air velocity of 10 m/s applied from hot air fluidized dryer obtained from pyrolysis process. The appropriate rice drying kinetics modeling has been selected based on the agreement between experimental results and seven drying kinetics equations available namely the drying kinetics modeling of Newton, Page, Henderson-Pabis, Logarithmic, Midilli, Two Term, and Verma. The degree of accuracy for the kinetics modeling is determined based on six statistics parameters namely the coefficient determination (R^2), mean absolute deviation (MAD), mean square error (MSE), root mean square error (RMSE), Akaike information criterion (AIC), and Schwarz information criterion (SIC). The results of the study show that the Verma drying kinetics modeling is the most appropriate model for rice using fluidized bed dryer with all given temperatures (50°C, 60°C, and 70°C) with regard to six given statistics parameters (R^2, MAD, MSE, RMSE, AIC, and SIC).

1. INTRODUCTION

Indonesia is the country with the most rice production in South East Asian around 132 kg/capita/year with the increased rice consumption of Indonesia achieved 1.6% per year [1]. By the reason of increase rice production every year, it needs a good management on post harvesting so that the rice product remains good and not easily damaged in rice stores or as it is distributed to customer [2]. The moisture content of post harvesting rice is approximately 20-23% wet basis at dry season and approximately 24-27% wet basis at rainy season. On the numbers of that moisture content rice cannot be safely stored due to fungi attack and can be damaged [3]. Rice with good quality has maximum moisture content of 14% wet basis [4].

The objective of rice drying is to reduce the moisture content in order to enhance rice quality and extend its storage time. The drying process is important in the management of post harvesting rice. The drying process is related to part of water removal from a material by water evaporation using heat energy [5]. The proposed fluidized bed dryer in this study is assumed to be effective and efficient. Fluidized bed dryer is a drying method broadly applied for drying wet particles and granule material using fluidized hot air. The benefit of the fluidized bed dryer is related to better solid mixing and has high rate of mass and heat transfer [6]. The important aspect in drying technology is involved with mathematics modeling of the drying process [7]. Therefore, this study investigates the drying kinetics modeling appropriate for rice applying fluidized bed dryer on the basis of statistical examinations.

Drying is a process related to reduction of moisture content of a solid matter by evaporation, blowing or heating at moderate temperature at normal or vacuum pressure [8]. Fluidized bed dryer is applied in many industries, such as mining, food, chemical and pharmaceutical industries [9]. The solid material used in drying process can be existed as powder, granules, crystals, plant seeds and even as slurry, paste, and suspension [6]. The particles will be fluidized in the dryer due to air stream [10]. The dryer operates with the drying temperature and drying rate of hot air and the solid material being dried will be fluidized and resulting the heat exchange rate getting faster [11]. The dryer has several advantages addressing to fast drying rate due to good contact between gas and solid as well as mass and heat transfer, shorter drying time, small drying device with large capacity, high thermal efficiency, low cost operation, easier monitoring, and so on [12, 13]. Previous study about the use of fluidized bed dryer about corn drying using a heat pump with heating air to dryer with minimum speed of fluidization is 1.54 m/s and air speed 13 m/s and temperature about 60°C [14]. Other study about the influence of hot air on drying quality purple rice using fluidized bed drying carried out with hot air temperature 150°C [15].

Thin layer drying is a kind of drying where the whole solid material assumed as a layer directly received drying air movement passing through the layer with relative humidity and constant temperature [16]. The thin layer drying is divided into three models namely the theoretical, empirical, and semi-empirical models [17]. The theoretical approach is related to diffusion equation, as well as heat and mass transfer equation simultaneously. The empirical model omitted the theoretical principals and directly presented the correlation between average water content and drying time by regression analysis. The semi-empirical model is an alternative way between the theoretical and empirical models, derived from simplification of the second Fick's law for diffusion, or as modification of the simplified model, such as Henderson-Pabis, Lewis/Newton, Page, Page modified models, and so on [18].

The earlier mathematical model used is the model developed by Newton and has already applied by previous researchers to present the drying kinetics of agricultural products [19]. The mathematical model is used to inform the exact profile of drying kinetics as one of steps in monitoring process and improving the overall process related to quality of final product. Several models are often used for the study of variables effect on the process, the prediction of drying kinetics of a product, and the optimization of operation parameters and condition [20]. The Newton kinetic model was used in the investigation of Westerman et al. [21] applying tray dryer for corn drying at high air temperature. The Page model for drying kinetic equation is a modified form of Newton kinetic equation that Page [22] added empirical exponential of time (n) into an equation described in report [23]. The Page kinetic model was used in the investigation of Page [22] applying tray dryer for corn drying at high air velocity. The Henderson-Pabis kinetic model was used in the investigation of Yagcioglu et al. [24] applying for bay leaf drying at temperatures of 50-60℃. The logarithmic drying kinetic model was used in the investigation of Chen et al. [25] the investigation used for granules drying applying fluidized bed dryer at drying temperatures of 50℃, 60℃ and 70℃ with air velocities of 2,63 m/s, 3,24 m/s and 3,56 m/s. The Midilli kinetic model (2001) [26] was used for pistachio drying applying solar drying at 50℃. The Midilli kinetic model was ever used in the investigation of Khanali et al., that the work was related to *Rice* drying applying fluidized bed dryer at drying temperatures of 50℃, 60℃ and 70℃ with air velocities of 2.3 m/s, 2.5 m/s and 2.8 m/s [27]. The Two Term kinetic model was used in the work of Suherman and Susanto [28], that the work was related to *Rice* drying applying fluidized bed dryer at temperature range of 50℃-90℃. The Verma drying kinetic model [29] was applied for *Rice* drying at two conditions, i.e, (i) using steam and (ii) without steam. The Verma drying kinetic model was also used in the work of Khanali et al. [27], that the work was used for *Rice* drying applying fluidized bed dryer at drying temperatures of 50℃, 60℃ and 70℃ and air velocities of 2.3 m/s, 2.5 m/s and 2.8 m/s. Several mathematical equations applied for thin layer drying are presented in Table 1.

Table 1. Models of drying kinetics [17, 25, 27, 28]

Model	Model equation
Newton	MR = exp (-kt)
Page	MR = exp (-kt^n)
Henderson & Pabis	MR = *a* exp (-kt)
Logaritma	MR = a exp (-kt+c)
Midilli et al	MR = a exp (-kt^n) + bt
Two Term	MR = a exp (-kt) + (1-a) exp (-akt)
Verma et al	MR = a exp (-kt) + (1-a) exp (-cbt)

where,

$$MR = \frac{M_t - M_e}{M_o - M_e} \tag{1}$$

The thin layer equation of Newton, Page, Henderson-Pabis, Logarithmic, Midilli, Two Term and Verma models are derived from Fick's second law for diffusion applied to depict the diffusion process. The second law of Fick has several assumptions as follows.

1. The material being dried exists as granules, isotropic, uniform size, and homogeneous.
2. The physical properties of solid material remain unchanged with drying time.
3. The granules contraction is omitted.
4. The humidity controls drying process.
5. The material is well mixed in fluidized bed.
6. The air is mixed perfectly.
7. The dryer device is perfectly isolated.

The aims of this study besides getting the effect of decreasing the moisture ratio and drying rate of rice on air temperature also get the most suitable drying mathematical model from 7 mathematical models at temperatures of 50℃, 60℃ and 70℃. Through this study, the findings of the mathematical equation model of drying are used as one of the steps in process control in scale up. The whole structure of this paper furthermore about the materials and method section consist of the raw material, the specification of the tools used, variables and the methods. The result and discussion part result of this study provided and thoroughly discussed. In the end of this article, the conclusion is provided the limitation and the future research direction to this topic.

2. MATERIALS AND METHODS

Rice as raw material obtained from Martubung area, Medan Labuhan, Medan, Sumatera Utara, Indonesia. The unit of fluidized bed dryer is integrated into pyrolysis apparatus. The heat is from biomass combustion process is flowed to fluidized bed dryer as a source of hot air in rice drying. The dryer chamber in dimensions of 50 cm x 30 cm x 100 cm equipped with cylinders where rice samples are placed. Blowers with specifications of 220 volts, 650 watts and speed of 0-15,000 rpm equipped by air speed controllers are used to drain and variation of air speed to the dryer chamber. Other equipment for data collection tool consisting of hygrometer, anemometer, electronic balance, and oven.

2.1 Procedure of rice drying using fluidized bed dryer

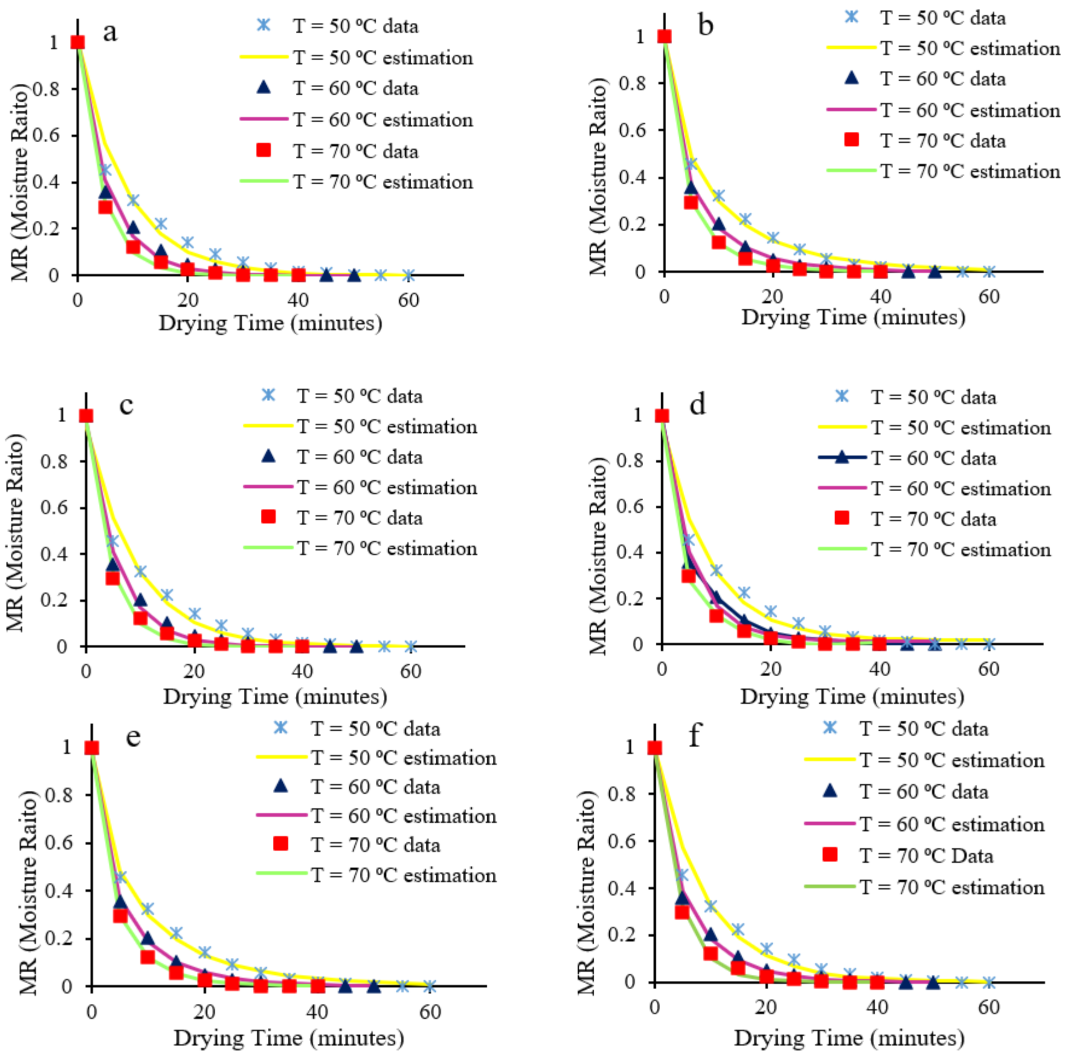
The rice sample is weighed with the bed height of 2 cm, 4 cm, and 6 cm and then put in the cylinders. Then the blower is turned on to drain hot air with temperatures variation of 50℃, 60℃ and 70℃ and the variation in air speed is set at 8 m/s, 9 m/s, and 10 m/s then the cylinders containing rice is placed into the drying chamber. Hot air temperature comes in, hot air temperature comes out, relative humidity (RH) comes in and RH comes out of the cross section of the cylinders and rice weight is measured every 5 minutes. The data obtained is recorded and then processed to obtain moisture ratio and drying rate and determination of equation constants in drying mathematical equations.

2.2 Procedure of determination of equation constants in drying mathematical equations

All data was managed to obtain the drying rate and estimated moisture ratio (MR) for each mathematical model respectively by previous research data according the procedure of rice drying using fluidized bed dryer. The determine of mathematical equation constant in drying model was conducted by trial-error applying Microsoft Excel 2013 and Solver Add-in program. By applying the software, the estimated MR will be obtained. Then, by comparing the experimental MR value and estimated MR value, the minimum value of total square of error and the drying constant for each model will be obtained. Furthermore, graphical presentation of MR and drying time from experiment and estimation for each model has been conducted and compared by each other. The error value of mathematical model is determined on the basis of determinant coefficient (R^2), Mean Absolute Deviation (MAD), Mean Square of Error (MSE), Root-Mean-Square Error (RMSE), Akaike Information Criterion (AIC) and Schwarz Information Criterion (SIC) in order to assay the suitable fit of each drying model proposed with the experimental results.

3. RESULT AND DISCUSSION

Drying has an influence on the quality characteristics of a product. The reason of variable that are varied in this study such as temperature (50°C, 60°C and 70°C) is organic materials that contain active substances will generally be damaged if heated at temperatures above 70°C and the air speed (8 m/s, 9 m/s and 10 m/s) is to get the appropriate temperature that is varied. The air speed and the temperature has a relationship. The higher the air speed the higher the temperature obtained. The use of simulation models/equations is important to predict the performance of the drying system. Drying equation thin layers can be used to predict drying curves in general. In the rice drying process, the thin layer equation is used. Thin layer drying process refers to the drying of particles or granules flowing with drying air [17]. By plotting moisture ratio (MR) and drying time obtained from experimental data and estimation data, Figure 1 show graphical presentations for various proposed drying kinetic models and the equation constants of each proposed drying kinetic model is presented in Table 2. Table 3 present the mathematical equation for each drying kinetic model applying the equation constant listed in Table 2. Analysis of the drying kinetics model was carried out by comparing the values of MRexp (Experimental Moisture Ratio) and MRestimation (Moisture Ratio Estimation) for each of the existing models. The main advantage of the modelling approach taken is that it has the ability to learn from experimental data. There are several empirical approaches to modelling the drying process of the drying process. In Figure 1 shows graphical presentation of experimental data and estimation data for proposed drying kinetic models such as Newton, Page, Henderson-Pabis, Logarithmic, Midilli, Two-Term and Verma where the moisture content of rice drying will reduce in longer drying time until its weight is constant. The advantage of the main model to apply and search for the right model due to its simplicity and usefulness makes up for the limitations.



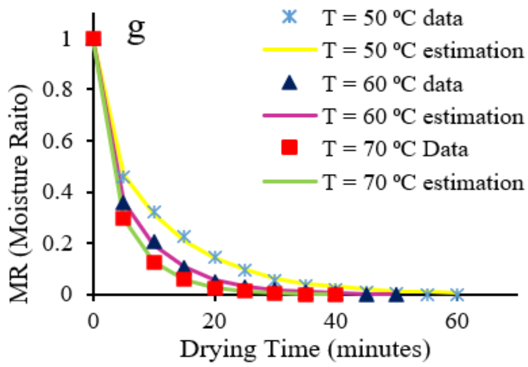


Figure 1. Graphical presentation of experimental data and estimation data for proposed drying kinetic models a) Newton, b) Page, c) Henderson-Pabis, d) Logarithmic, e) Midilli, f) Two-Term and g) Verma

Table 2. Mathematical equation constants of proposed drying kinetic models

Parameter	Temp. (°C)	Proposed Drying Kinetic Model						
		Newton	**Page**	**Henderson-Pabis**	**Logarithmic**	**Midilli**	**Two-Term**	**Verma**
	50	0,1145	0,2173	0,1095	0,1169	0,2153	0,1221	0,0802
k	60	0,1771	0,2961	0,1749	0,1835	0,2957	0,4628	0,1235
	70	0,2288	0,3408	0,2280	0,1703	0,3408	0,2289	0,1689
	50	-	0,7441	-	-	0,7463	-	-
n	60	-	0,7562	-	-	0,7565	-	-
	70	-	0,7912	-	-	0,7913	-	-
	50	-	-	0,9584	0,9495	0,9959	0,7188	0,6970
a	60	-	-	0,9865	0,9766	0,9992	0,2929	0,6693
	70	-	-	0,9956	0,4613	0,9999	0,9833	0,6845
	50	-	-	-	-	-	-	2,0989
b	60	-	-	-	-	-	-	10,663
	70	-	-	-	-	-	-	44,724
	50	-	-	-	0,0164	-	-	2,0989
c	60	-	-	-	0,0129	-	-	1
	70	-	-	-	0,5189	-	-	1

Table 3. Drying kinetic equation for proposed drying models

Model	Temp. (°C)	Mathematical equation model
	50	MR = exp (-0,1145t)
Newton	60	MR = exp (-0,1771t)
	70	MR = exp (-0,2288t)
	50	MR = exp ($-0,2173t^{0,7441}$)
Page	60	MR = exp ($-0,2961t^{0,7562}$)
	70	MR = exp ($-0,3408t^{0,7912}$)
	50	MR= 0,9584 exp (-0,1095t)
Henderson-Pabis	60	MR= 0,9865 exp (-0,1749t)
	70	MR= 0,9956 exp (-0,2280t)
	50	MR = 0,9495 exp (-0,1169t) + 0,0164
Logarithmic	60	MR = 0,9766 exp (-0,1835t) + 0,0129
	70	MR = 0,4613 exp (-0,1703t) + 0,5189
	50	MR = 0,9959 exp ($-0,2153t^{0,7463}$)
Midilli	60	MR = 0,9992 exp ($-0,2957t^{0,7565}$)
	70	MR = 0,9999 exp ($-0,3408t^{0,7913}$)
	50	MR = 0,7188 exp (-0,1221t) + 0,2812 exp (-0,0878t)
Two Term	60	MR = 0,2929 exp (-0,4628t) + 0,7071 exp (-0,1355t)
	70	MR = 0,9833 exp (-0,2289t) + 0,0167 exp (-0,2251t)
	50	MR = 0,6970 exp (-0,0802t) + 0,303 exp (-4,4054t)
Verma	60	MR = 0,6693 exp (-0,1235t) + 0,3307 exp (-10,663t)
	70	MR = 0,6845 exp (-0,1689t) + 0,3155 exp (-44,724t)

3.1 Evaluation results of various proposed drying kinetic models

Each proposed drying kinetic model is necessary to be assayed its suitable fit model to determine the most appropriate model applying statistical parameters such as MAD and RMSE [30]. The realization in accuracy in applying some of these drying kinetics models may not be very high. This is because the errors may be close, but these results are well accepted. By applying the six proposed statistical parameters (R^2, MAD, MSE, RMSE, AIC, and SIC), the results are shown in Table 4.

Table 4. The suitable fit test for proposed drying kinetic models at 70°C applying statistical examination

Statistical Parameter	Drying kinetic model						
	Newton	Page	Henderson-Pabis	Logarithmic	Midilli	Two-Term	Verma
R^2	0.9977	0.9999	0.9978	0.9991	0.9999	0.9977	0.9999
MAD	0.0052	0.0029	0.0056	0.0033	0.0012	0.0052	0.0005
MSE	0.0002	0.0002	0.0002	$8.7x10^{-5}$	$5.6x10^{-5}$	0,0002	$3.2x10^{-6}$
RMSE	0.0146	0.0127	0.0146	0.0094	0.0075	0.0146	0.0018
AIC	0.0003	0.0003	0.0003	0.0002	0.0029	0.0146	$7.8x10^{-6}$
SIC	0.0003	0.0003	0.0003	0.0002	0.0049	0.0006	$8.5x10^{-6}$

Table 4 show that all drying kinetic models have R^2 value with the range of 0.9877 – 0.9999. The R^2 value in the range of 0 – 1. If the R^2 value close to 1, it shows that the model is appropriate [31]. With regard to MAD examination, the Verma drying kinetic model shows the lowest value of all drying models in the range of 0.0005 – 0.0,0056. MAD shows a deviation value from the mean data [32]. Small MAD value shows small error of that given model. Furthermore, the MSE values of Verma drying kinetic model show the lowest values for given temperatures namely 3.2 x 10^{-6}. MSE is the average of difference values between experimental and estimation data in quadratic form [33] and therefore, it can be said that the smaller MSE value shows the suitable model.

With regard to RMSE value, the Verma drying kinetic model shows the lowest value of all proposed drying kinetic models at same condition. Low RMSE value indicates that the model is appropriate [34]. The RMSE values for Verma drying kinetic model at 70°C are found to be 0.0018.

The efficiency of several drying kinetic models can be examined based on their AIC values. Moreover, the selection of the best model can be proven from the low AIC value of each model [35]. This study shows that the Verma drying kinetic model shows the lowest value of AIC. According to SIC, the best regression model is the model with the lowest SIC value [36]. The Verma drying kinetic model shows the lowest SIC value in this study, i.e. for temperatures of 70°C show SIC values of 8.5 x 10^{-6}, respectively. The small SIC value indicates the model is acceptable and the Verma model fulfilled the requirement.

4. CONCLUSION

Rice drying using fluidized bed drying can be applied. Based on this research an increase in temperature during drying can affect the drying time. The use of simulation models/equations is important to predict the performance of the drying system. On the basis of six kinds of simulation equation, it can be concluded that the Verma drying kinetic model is the best fit model shown in this study for rice drying by applied with fluidized bed drying. The related mathematical equations meet the requirements are as follows:

T = 50°C	MR = 0,6970 exp (-0,0802t) + 0,303 exp (-4,4054t)
T = 60°C	MR = 0,6693 exp (-0,1235t) + 0,3307 exp (-10,663t)
T = 70°C	MR = 0,6845 exp (-0,1689t) + 0,3155 exp (-44,724t)

The future research direction can involve in the next step after define the optimum temperature then for the purpose of scale up in rice drying process.

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