Journal of Engineering and Applied Sciences 14 (24): 9592-9597, 2019
ISSN: 1816-949X

Effect of Temperature on Effective Moisture Diffusivity in Paddy Drying with Dehumidified Air

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Abstract: This research discusses the effective moisture diffusivity on paddy drying with air dehumidified by zeolite. The paddy with an initial moisture content of 22% (wet basis) was dried in fluidized bed dryer at different temperature ranging 40-60°C. As a response, the moisture content in paddy was observed every 10 min for operational drying time 90 min. In doing so, a mathematical model was developed to predict the effective moisture diffusivity that was validated with average moisture content from the experiment. Result showed that the effective moisture diffusivity of paddy dried with zeolite was higher than that of without zeolite. The model also can fit with the experiment and be able to describe the moisture distribution accurately. Moreover, the quality of paddy based on proximate analysis during the drying process was acceptable and comparable with the quality of paddy dried without zeolite.

Key words: Paddy drying, effective moisture diffusivity, zeolite, drying time, accurately, distribution

INTRODUCTION

One of the major economic crops that produces and consumes to provide food supply in several countries is paddy. The major operations for paddy processing involve soaking, parboiling or steaming, drying and milling. The quality of post harvested paddy can be kept by the drying process. The drying process by reduction of moisture content can be an option to prolong the shelf life of food product. The shelf life of paddy can be extended until 18 month when the maximum moisture content is 14% (Morrison *et al*., 2016).

Today, there are two methods of paddy drying: direct sunlight and conventional dryer. Because of its simplicity and low energy cost, the direct sunlight drying is commonly used by farmers (Djaeni *et al*., 2014). Conventional dryers such as a fluidized bed have more advantages such as controlable process, uniform moisture content of the product, shorter operational time because of high surface area, no dependency on the climate, low product contamination, low initial cost and small space usage because of small equipment (Djaeni *et al*., 2015; Kiranoudis *et al*., 1996).

Mathematical model is the important aspect to characterize drying process in paddy, since, it is useful to find the favorable drying condition as well as effective drying time. The fundamental of drying model and simulation can predict the important paramaters for the drying process (Gunhan *et al*., 2005). Several paddy drying can be described using two term, page or modified page models (Omid *et al*., 2006; Utari *et al*., 2018; Manikantan *et al*., 2014; Laohavanich and Wongpichet, 2008). The models were proper to represent thin layer drying in which useful to determine drying time. Thin layer drying is the simple model that assumes the sample as the one layer or slices particle with uniform temperature distribution (Erbay and Icier, 2010). In paddy drying there are two different layers, the outer and the inner layer with different characteristics. In this study, the mathematical model was developed to expose the paddy layers characteristics. The finding of this study will give new approach in paddy drying characterization.

The aim of this study was to evaluate the effect of temperature and air dehumidified with zeolite in paddy drying. A mathematical model was developed to estimate effective moisture diffusivity and predict moisture content distribution in paddy layer during the drying. The model was fitted with experimental data in order to be accurate to predict the drying time of paddy at various air condition. Beside that the proximates were evaluated after the completion of the drying process.

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MATERIALS AND METHODS

Paddy drying

Material: Paddy was obtained from a local farmer in Semarang at the initial moisture content about 22% (w/w) or 0.28 (dry basis, gr water per gram dry paddy). The zeolite 3A (provided by Zeochem, Switzerland) was used as an adsorbent to dehumidify ambient air as drying medium. The sensor of KW0600561, Krisbow®, Indonesia was used for measuring air temperature anda relative humidity. The air velocity was measured by KRISBOW instruments Anemometer KW06562. The water content in paddy was analyzed using a grain moisture meter G-Won GMK-303RS.

Experimental set-up: The paddy drying system was designed as a fluidized bed dryer (Fig. 1). The dryer was equipped with a blower to deliver air for the fluidization process. Initially, ambient air at a Relative Humidity (RH) of 70-80%, air veolcity of 5.51 msec^{-1} and temperature about 28-31°C was contacted with the zeolite column to reduce the moisture content. The dry air was then heated up to dryer temperature (supposed at 40°C). The 100 g of paddy with initial moisture content about 22% (w/w) or 0.28 (dry basis) was dried with the air. Every 10 min, the moisture content in the paddy was observed using a grain moisture meter G-Won GMK-303RS for 90 min. After the drying process, the proximates in paddy were analyzed including protein, carbohydrat and fat. The process was repeated for the inlet air temperature of 50 and 60°C.

Moisture ratio calculation: The equilibrium moisture content of paddy was estimated using the modified Henderson Model (Thompson *et al.*, 1968):

$$C_{E,wb} = \left[\mathrm{In}\left(1-H_R\right)/\left(-K\left(T_C+M\right)\right)\right]^{1/N} \tag{1}$$

$$C_E = \frac{C_{E,wb}}{1-C_{E,wb}} \tag{2}$$

Where:

$C_{E,wb}$ = The equilibrium moisture Content of paddy in wet basis (%)
C_E = The equilibrium moisture Content of paddy in dry basis (gr water per gram dry paddy)
H_R = The relative Humidity (decimal)
T_C = The air Temperature (C) with K, L and M values as follows (Nguyen *et al.*, 2016):

$$K = 1.9187\times10^{-5}$$
$$L = 2.4451$$
$$M = 51.161$$

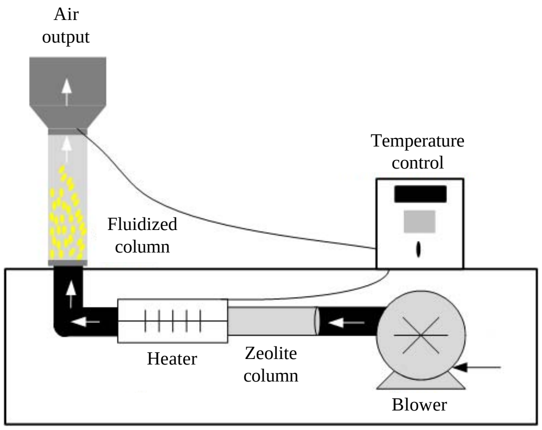

Fig. 1: The fluidized bed drying equipment according to (Djaeni *et al.*, 2013) with modification

The moisture ratio during the drying process can be estimated based on the moisture content observation every sampling time. The following equation was used (Nguyen *et al.*, 2016):

$$MR = \frac{\left(C-C_E\right)}{\left(C_0-C_E\right)} \tag{3}$$

Where:

C = The moisture content at time t min (gr water per gram dry paddy)
C_0 = The initial oisture content (gr water per gram dry paddy) at the 0 min

Mathematical model: A mathematical model was developed to predict the effective moisture diffusivity (D_{eff}), constant rate of the drying (k) and the moisture mass distribution in paddy drying. The model was derived based on phenomena as illustrated in Fig. 2. Based on Fig. 2, the differential equation for cylindric can be applied (Bird *et al.*, 2007).

The following assumptions was used before developing the models: the grain material was a cylinder (Fig. 2), the effective moisture diffusivity and the density of water in solid were constant, the initial water content was uniform in all sections of paddy grain, the water diffused in the radial direction, the air velocity was uniform in all sections of the drying column, the heater temperature was uniform in all sections of the drying column, the air and paddy mixture was homogenous system and one paddy grain represented all dried paddy grain materials. The models can be represented in Eq. 4-9:

$$\frac{\partial C}{\partial t} = D_{eff}\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial C}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 C}{\partial \theta^2}+\frac{\partial^2 C}{\partial z^2}\right) \tag{4}$$

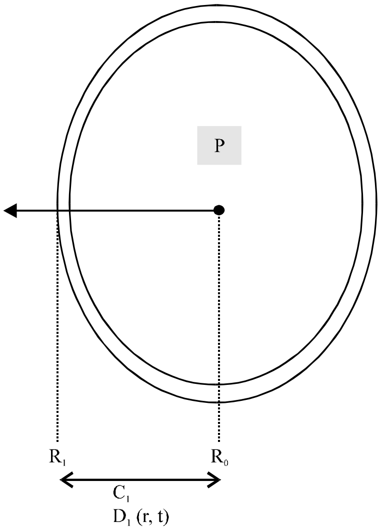

Fig. 2: Diffusion on paddy drying

$$\frac{\partial C}{\partial t} = D_{eff}\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial C}{\partial r}\right)\right) \quad (5)$$

$$\frac{\partial C}{\partial t} = D_{eff}\frac{1}{r}\left(\frac{\partial C}{\partial r} + r\frac{\partial^2 C}{\partial r^2}\right) \quad (6)$$

$$\frac{\partial C}{\partial t} = D_{eff}\left(\frac{\partial^2 C}{\partial r^2} + \frac{1}{r}\frac{\partial C}{\partial r}\right) \quad (7)$$

The boundary condition was used to describe the cylindric material as follow: boundary condition in the center paddy circle, $r = R_0$, $t>0$:

$$\frac{\partial C}{\partial t} = 0 \quad (8)$$

Boundary condition in outer layer of paddy, $r = R_1$, $t>0$:

$$\frac{\partial C}{\partial t} = k\left(C - C_E\right) \quad (9)$$

Where:

D_{eff} = The effective moisture diffusivity (m^2/sec-1)
r = The paddy layer
k = The constant rate of the drying (min-1)

The value of D_{eff} and k were obtained by Excel Solver and validated by the average moisture content referring to experiment data. Temperature dependence of effective moisture diffusivity can be given by an Arrhenius Model, as shown in Eq. 10:

$$D_{eff} = D_0 e^{\left(-\frac{Ea}{RT_K}\right)} \quad (10)$$

where D_0 was the pre-exponential factor of the Arrhenius equation Ea was the activation energy (kJ.mol-1) R was the universal gas constant (0.008314 kJ.mol-1.K-1) and T_k was the absolute air temperature (K).

RESULTS AND DISCUSSION

Effect of temperature and zeolite: The moisture ratio versus time was observed as depicted in Fig. 3. At same sampling time and operational temperature, the paddy drying with zeolite resulted lower moisture content as indicated in lower moisture ratio. With zeolite, the air was dehumidified to the low moisture content. Hence, the relative humidity of air becomes lower that enhanced driving force for drying (Djaeni *et al*., 2013; Utari *et al*., 2018). Using zeolite as air dehumidifier, the drying process has two advantages as follows: zeolite lowers the air humidity in which increases the driving force for drying and lowering air humidity increases air temperature due to the adsorption heat (Djaeni *et al*., 2011, 2013). With these advantages, the paddy drying can be more effective.

The proximate was observed after the completion of the drying process. The results showed that the content of fat, protein and carbohydrate were still comparable with the other drying method (Table 1). The heat sensitive compounds in paddy are protein and glucose groups. The companents can combine to form browning process (Lamberts *et al*., 2006). Meanwhile, the protein denaturation can be posible, especially for operating temperature above 70°C (Bischof and He, 2005; Ovissipour *et al*., 2017). However, under low drying temperature ranging from 40-60°C, the protein denaturation can be inhibitted. Thus, the paddy quality is still acceptable.

For all cases, the increase of temperature can also reduce the relative humidity of air. Therefore, the drying rate becomes faster or more water can be removed from the product. Beside that at higher drying temperatures, the air brings more sensible heat that can be used to evaporate water from the wet paddy. Hence, at higher operational temperature (supposed above 80°C), the effect of dehumidified air is not significant (Djaeni *et al*., 2015). However, at higher temperature, the heat sensitive ingredients can deteriorate.

Model validation and moisture mass distribution profile: Based Fig. 3, the effective moisture diffusivity for every operational temperature was estimated using Eq. 4-9. As

Djaeni *et al*., 2018; Rayaguru and Routray, 2010). Temperature dependence of moisture effective diffusivity was well correlated using Arrhenius equation. As the the indicators, the coefficient of determination (R^2) and Sum of the Squared Error (SSE) were evaluated. The R^2 and SSE were calculated based on the different between the average moisture content estimated by model with experiment data. The average moisture content was estimated by considering the level of moisture in every paddy layer. The accurate effective moisture diffusivity was chosen when the value of R^2 closes to 1.0 with low SSE value. The results were depicted in Table 2 for all drying temperature. The average mositure content in paddy obtained by model and experiment for 40°C are illustrated in Fig. 4 that indicate the trendline of the moisture profile are similar.

Table 1: Proximate analysis result

	Content (%)			
Samples	Ash	Fat	Protein	Carbohydrate
Zeolite 40°C	11.18	0.73	6.73	66.83
Zeolite 60°C	11.10	0.73	6.73	66.86
Non-zeolite 40°C	11.24	0.71	6.75	66.80
Non-zeolite 60°C	11.32	0.70	6.76	66.32

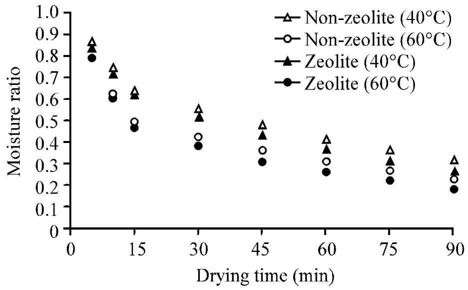

Fig. 3: Moisture content at different drying times and temperatures

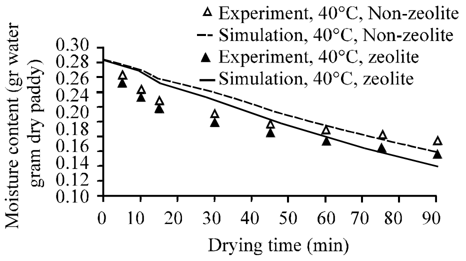

Fig. 4: Experimental and simulation moisture content at T = 40°C

With the zeolite, the moisture diffusivity as well as constant of drying rate at the surface of paddy was higher than that of without zeolite. Hence, the drying time can be faster. Meanwhile, for all cases, the increase of temperature also resulted higher effective moisture diffusivity coefficient as well as constant of drying rate. With the increase of temperature, the movement of moisture molecules in the surface and tissue layers of paddy is accelarated. By the zeolite or increasing temperature, the relative humidity of air becomes lower. Hence, the water activity different between product and air becomes higher that can increase the water transfer from wet product to the air (Bouzenada *et al*., 2014; moisture diffusivity increase, the activation Energy (Ea) in drying with zeolite can be reduced. Compared with the other research results, the combination of air dehumidification and the increase of air temperature up to 60°C as performed in this study can find positive improvement (Golmohammadi *et al*., 2016; Oli *et al*., 2014;

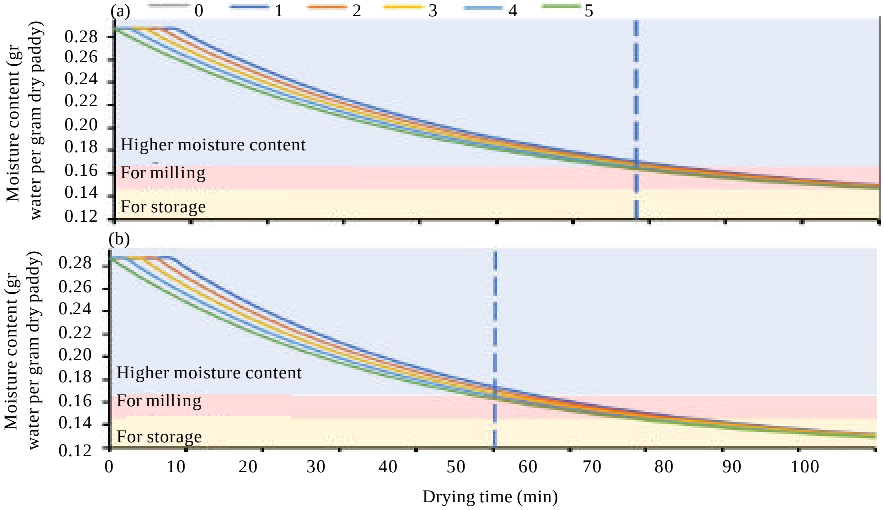

Fig. 5: Moisture mass distribution at T = 40°C: a) Without zeolite and b) With zeolite (note number 0-5 represent paddy layers)

Table 2: Paddy drying constant (D_{eff} and k) and statistical parameter for simulation

	Non-zeolite				Zeolite			
Temperature (°C)	D_{eff} (m^2/min)	k	R^2	SSE	D_{eff} (m^2/min)	k	R^2	SSE
40	1.000×10^{-8}	0.022	0.888	0.003	7.626×10^{-8}	0.025	0.897	0.004
50	1.010×10^{-7}	0.024	0.832	0.008	4.881×10^{-7}	0.032	0.864	0.008
60	1.000×10^{-6}	0.031	0.852	0.011	1.000×10^{-5}	0.039	0.856	0.010

Tirawanichakul *et al*., 2014). The model with effective moisture diffusivity estimation was validated by average moisture content in paddy from experiment. The valid paramater can be used for predicting moisture level at every layer of paddy. For example, the paddy was dried at 40°C for 100 min. The simulation results are expressed in Fig. 5. At first 30 min, the moisture level in paddy layers decreased gradually corresponding to the layer position. The surface of paddy (outer layer) has lowest moisture content, since, the moisture evaporates to the air. So, the moisture moves from inside to the outer layer. In paddy drying, the process was run until average moisture content achieving 14% wet basis or 0.16 dry basis. This condition is preferable both for paddy storing or milling. In this case with the zeolite, to dry paddy from moisture content 22% up to 14% needs around 50 min. The process was 18-20 shorter than the drying without zeolite. This result is comparable with the other product dried with zeolite or air dehumidification (Djaeni *et al*., 2014; Osorio-Revilla *et al*., 2006; Goudra *et al*., 2014).

CONCLUSION

This study showed that zeolite improves the driving force for paddy drying. At same operational time and temperature, the water transferred from wet paddy is higher compared to the paddy drying without zeolite. In addition, the proximate in paddy after the drying is acceptable and still comparable with the other drying method. However, at higher drying temperatures, the relative humidity of air is also low. Therefore, the effect of the zeolite is not significant. The effective moisture difussivity has been also predicted. Result showed that the effective moisture diffusivity of paddy dried with zeolite was higher than that of without zeolite. The model also can fit with the experiment and be able to describe the moisture distribution accurately.

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