Experimental Study and Mathematical Quantification of Drying as Pretreatment of Local Biomass for Adsorbents in Biogas Purification

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Abstract: Biogas impurities is a major problem related to its heating value and feasibility of conversion to small-scale electrical energy. Adsorption is believed as one of the potential method of biogas purification. This process conducted in porous material whose surface active properties, such as activated carbon with an acid or base activator. Laboratory experiments and mathematical quantification were carried out to study the drying process of Gamal (Gliricidia sepium) stem as a source of biomass that were widely grown in the local area of livestock / biodigester. Determination of the drying process parameters and mass transfer parameters were approached using three drying models: (1) Dincer and Dost models, (2) Bi-G correlation approach, and (3) Fick's law equation. This research shows that second Fick's Law is the best model to describe the drying process parameters and to calculate the mass transfer parameters for Gamal stem.

1 INTRODUCTION

Drying, an energy intensive process, involves both heat and mass transfer (Ndukwu, 2017). Drying can be done by traditional and modern drying method, there are sun drying and oven drying (Ramavandi, 2015). The most common traditional drying is using solar heat because it costs more reasonable price and easy to practice (Afolabi, 2014). Drying using hot air widely used in industries because it is more efficient in time (Fernando, 2016). Arredondo (2016) argued that cylinders in shape has lower energy consumptions due to their fast moisture removal.

The drying process of wood has two stages, the first stage is moisture transfer from the inner wood as capillary flow and diffusion to the surface. Then the second stage is water evaporation from the wood surface to the environmental or drying medium (Zhengbin, 2019). Moisture transfer coefficient and effective moisture diffusivity are used to analyse the efficiency of mass transfer and drying moisture transfer model (Harchegani, 2014). By measuring the weight loss of samples at time interval, moisture losses during drying process can be determined (Akonor, 2016).

Alara (2017) said the most important aspect of drying technology is the mathematical modelling of drying processes. The mathematical modelling is used to arrange several equations to describe a system (Sridhar, 2015).

In this research, drying processes were conducted in electrical oven. In theoretical consideration, three moisture transfer models, including: Dincer and Dost model, Bi-G correlation approach, and conventional solution of second Fick's law of diffusion were used to determine effective moisture diffusivity and moisture transfer coefficient. The modelling is basically based on a set of mathematical equations which can explain the drying system and the solution of these equations must allow the prediction of the process parameters as the function of time at any point of the dryer which is basically depending only on the initial condition (Nurafifah, 2018).

2 MATERIAL AND METHODS

This research uses several instruments, such as:

- Woodcutter machines. It was used to cut the raw material into 3 cm of length.
- Oven. This research use oven for drying process.
- Calipers. It has been used to measure the diameter of the raw material.
- Petri dishes. During the drying process, the raw materials was put into petri dishes.

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2.1 Materials

Wood stems of Gliricidia sepium from local area and assumed to be cylindrical in shape were used.

2.2 Experimental Procedure

This research was divided into three steps. There are (1) raw material preparation, Gliricidia sepium was cut into various diameter which are 13 cm, 16 cm, and 18 cm. Each variation has 3 cm length, (2) oven drying, the sample is weighed and placed in a different petri dish for each diameter. The sample is dried in the oven at 100ºC and weighed every 10 minutes, and (3) calculation of the experimental data, the sample weight losses data was obtained and then the experimental data will be compared to calculate the drying rate.

2.3 Mathematical Modeling

2.3.1 Model I: Dincer and Dost Model

In this model, the transient moisture diffusion process is similar to the heat conduction process in entire drying process. The different geometric-shaped of the raw material/moist solid can be determined by Dincer and Dost equation (Harchegani, 2014). The time-dependent moisture diffusivity equation in one-dimensional cylindrical coordinates for an infinite cylinder can be written as follow:

$$\left(\frac{1}{r^1}\right)\left(\frac{\partial}{\partial r}\right)\left(r^1\frac{\partial M}{\partial r}\right) = \left(\frac{1}{D}\right)\left(\frac{\partial M}{\partial t}\right) \quad (1)$$

Initial and boundary condition:

$$\phi\,(r,0) = \phi_i = (M_i - M_e),$$

$$\frac{\partial}{\partial r}\phi(0,t) = 0, -D\left(\frac{\partial}{\partial r}\phi(Y,t)\right) = k(\phi(Y,t) - \phi_0) \quad (2)$$

Biot and Fourier dimensionless number:

$$B_i = kL/D \quad (3)$$

$$F_o = Dt/L^2 \quad (4)$$

The moisture ratio at any point of the solid can be expressed as follow (Lingayat, 2016):

$$\phi = (M - M_e)/(M_i - M_e) \quad (5)$$

The solution in equation (1) with the dimensionless humidity distribution centre boundary conditions for an object

$$\phi = \sum_{n=1}^{\infty} A_n B_n \quad (6)$$

The solution of equation (1) with the boundary conditions yields dimensionless centre moisture distribution is

$$\phi \cong A_1 B_1 \quad (7)$$

For an infinite cylindrical object:

$$A_1 = G = \exp[0.5066Bi/(1.7 + Bi)] \quad (8)$$

$$B_1 = \exp(-\mu_1^2 F_o) \quad (9)$$

The characteristic in equation (9) is given by Dincer and Dost as follow:

For an infinite cylindrical object:

$$\mu_1 = ((3/4.188)\ln(6.796B_i + 1))^{1/1.4} \quad (10)$$

For $0.1 < Bi < 10$

The exponential form can be used to express dimensionless moisture distribution.

$$\phi = G\exp(-St) \quad (11)$$

where G represents lag factor (dimensionless) which indicate an internal resistance of an object to the heat and/or moisture transfer during drying and S represents drying coefficient that shows the drying capability of an object per unit time (1/s).

The moisture diffusivity for an infinite slab, cylinder or spherical products is given by the following equation below:

$$D = SY^2/\mu_1^2 \quad (12)$$

The moisture transfer coefficients results can be express in

$$k = (DBi/Y) \quad (13)$$

And to determine the moisture transfer coefficient for an infinite cylindrical object can be written as follow:

$$k = (D/Y)[(1 - 1.974\ln G)/(3.3559\ln G)] \quad (14)$$

2.3.2 Model II: Bi-G Correlation

Biot number–lag factor (Bi–G) correlation is proposed by Dincer and Dost and has been used to determine the mass transfer parameters (Harchegani, 2014).

$$Bi = 0.0576\,G^{26.7} \quad (15)$$

1. The characteristic first root in equation (9) is determined using the following expression below for infinite cylindrical object.

$$\mu_1 = -3.4775G^4 + 25.285G^3 - 68.43G^2 + 82.468G - 35.638 \quad (16)$$

The procedure of using Dincer and Dost and Bi-G Correlation modelling technique for estimating the process parameters and drying parameters is as follows:

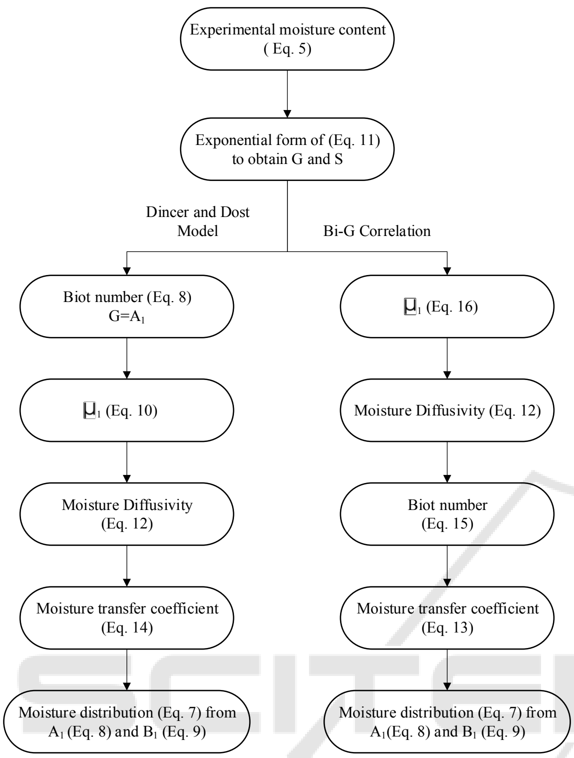

Figure 1.

2.3.3 Model III: Second Fick's Law

Second Fick's law can be used to study water diffusion kinetics and effective moisture diffusivities (Demiray, 2017).

Crank's solution of second Fick's law has been used by many authors to determine effective moisture diffusivity by assuming uniform moisture distribution

$$MR = \sum_{n=1}^{\infty} \frac{4}{r^2 \alpha_n^2} \exp(-D_{eff} \alpha_n^2 t) \quad (17)$$

where n is the number of terms in Fourier series.

The convective mass transfer coefficient was described by Kaya et al. as follow:

$$k_m = -\frac{V}{At} \ln(MR) \quad (18)$$

where A and V are the sample surface area (m^2) and the sample volume (m^3).

To determine the samples drying parameters, we can use the conventional solution of second Fick's law as follow:

- Result log of equation 17
- Plot the experimental data of ln(MR) versus the drying time then calculate the moisture diffusivity.
- $D = \left(-\frac{R^2}{\pi^2}\right) x\ (straight - line\ slope) \quad (19)$
- The convective mass transfer coefficient was determined using Eq. 18
- Calculate the moisture ratio values.

2.3.4 Analysis

Determination of the best model for mathematical quantification of drying of gamal stem will be done through statistical criteria, root of mean square error (RMSE) and coe□cient of determination (R) (Azeez, 2019). Dhanushkodi (2017) explained that RMSE and R can be solved by this equation below:

$$\text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left(MR_{exp,i} - MR_{pre,i}\right)^2} \quad (20)$$

$$R^2 = \frac{\left[\sum_{i=1}^{N} (MR_{exp,i} - \overline{MR_{exp}})\,(MR_{pre,i} - \overline{MR_{pre}})\right]^2}{\sum_{i=1}^{N} \,(MR_{exp,i} - \overline{MR_{pre}})^2 \sum_{i=1}^{N} (MR_{exp,i} - \overline{MR_{pre}})^2} \quad (21)$$

3 RESULTS AND DISCUSSION

3.1 Drying Kinetics

The equilibrium moisture content of the biomass sample for different diameter is determined with a temperature of 100oC during the drying period and reached when there is no significant change in sample weight. Drying time for each sample are 210, 240, 240 minutes for the drying process carried out respectively on the sample diameter of 13, 16, 18 mm. To reach equilibrium moisture content, Figure (2) shows the ratio between humidity vs time for different sample diameters. The graph shows an exponential trend for the drying curve. Lowest diameter (13 mm) requires the shortest time to reach entire equilibrium moisture content. Larger diameter has a larger contact surface area but contains more moisture content so it requires a longer time.

Generally drying takes place in two periods, a constant rate and a period of falling rates. After a warm-up period, a constant rate occurs and is followed by a period of slowing down. Usually, in a

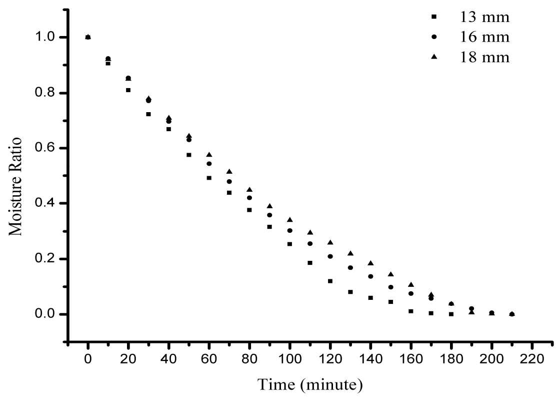

Figure 2 : Moisture ratio of sample drying vs time with a diameter difference.

constant period, there is a reduction of moisture on the surface.

The drying rate during this period mostly depends on the rate of heat transfer to the material that being dried. Therefore, the maximum drying rate that can be reached is considered a limited heat transfer. If drying is continued, the slope of the drying rate curve becomes less steep (period of falling rate), and finally tends to be almost horizontal for a very long time.

3.2 Model Application: Moisture Diffusivity and Moisture Transfer Coefficient Estimation

By using the least-squares method, the dimensionless values of the experimental moisture ratio were regressed against the drying time according to equation (11) and the drying coefficient (S) and the lag factor (G) were obtained. Values of R^2 and RMSE indicate that the exponential equation satisfactorily fitted to the experimental data. The drying coefficient values obtained are shown in (Table 1).

The drying coefficient shows the drying ability of a product per unit time. The values of lag factor (1.1892, 1.1982, and 1.2151) for the diameter of the samples respectively 13, 16, 18 mm more than 1 indicating the diffusion of humidity in the sample is controlled by internal and external resistance.

Table 2: Drying coefficient (S) and Lag factor (G), MR = G exp (-S t).

Diameter (mm)	G	S (h^{-1})	R^2	RMSE
13	1,1892	1,3642	0,8391	0,1271
16	1,1982	1,1044	0,9005	0,0992
18	1,2151	1,1392	0,8304	0,1271

3.2.1 Dincer and Dost Models (Model I) and Bi-G Correlation (Model II)

Biot (Bi) number values, the first root of the transcendental characteristic equation (μ1), moisture diffusivity (D) and moisture transfer convective coefficient (km) obtained by the Dincer and Dost model (Model I) and the Bi-G correlation (Model II) is presented in Table (2).

Biot numbers is one of the most important parameters during the drying process and show the main moisture transfer mechanism in the material. Very small Biot numbers, < 0.1, indicate that mass transfer is externally controlled, while Biot numbers > 0.1 indicate the presence of both internal resistance (due to the sample itself) and surface resistance (due to boundary layers) for moisture transfer. Biot number values by both models I and II show that these characteristics depend on the diameter of the sample and increase with increasing diameter. The moisture diffusivity of each diameter was calculated by Model I and Model II by equation (12) and the results are shown in Table (2). The humidity diffusivity values of Model I and Model II with differences in diameter

Table 1: Results of Calculation of Mass Transfer Parameters with Dincer and Dost models (Model I) and Bi-G correlation (Model II).

Parameter	13mm		16mm		18mm	
	model 1	model 2	model 1	model 2	model 1	model 2
Bi	0,883800638	5,885382432	0,943972494	7,206677355	1,062701427	10,47264355
D ($m^2 h^{-1}$)	5,80877E-05	3,82202E-05	6,72587E-05	4,4526E-05	7,94096E-05	5,32643E-05
μ1	0,996116992	1,228021522	1,025141704	1,259943676	1,077992197	1,316236551
km ($m h^{-1}$)	0,000303603	0,006652639	0,000291341	0,005895662	0,000315262	0,005568645

are 5.80877E-05; 3.82202E-05; 4,4526E-05; 5,32643E-05 for model II for diameters of 3, 16, 18 mm.

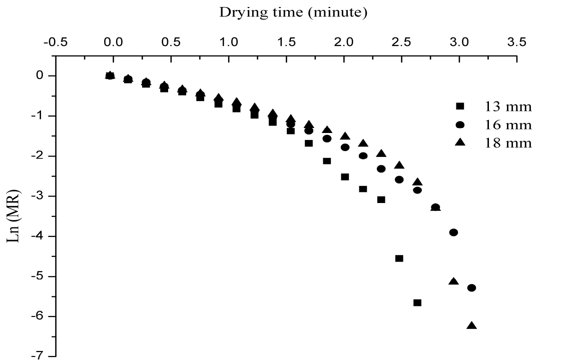

Figure 3: The relationship of Ln(MR) to the drying time on the difference in sample diameter.

Moisture transfer convective coefficient for drying application is determined based on the values of G, Bi and D with models I and Model II using equations (13) and (14). The parameter value of the moisture transfer convective coefficient ranges from 0.000291341-0.000315262 m h-1 for models I and 0.005568645-0.006652639 m h-1 for model II at each diameter.

3.2.2 Second Fick's Law (Model III)

By plotting ln(MR) and drying time and then using the gradient of the graph in Figure (3), the effective diffusivity value of humidity with equation (17) with a variety of sample diameter is obtained. The effective diffusivity values of humidity are obtained in Table (3). The values range from 1.19656E-05 - 1.93599E-05 m2 h-1. And the value of convective mass transfer coefficient (Km) with moisture content for the variation of sample diameter are illustrated in Figure (4). The obtained values ranged between 0.003881654 - 0.012967475 (average value 0.006184313) m h-1, 0.003771573 - 0.012697894 (average value 0.005628793) m h-1, 0.004383745 - 0.016848745 (average value 0.005750302) m h-1 for samples with diameters of 13, 16, 18 mm.

Table 3: Mass Transfer Calculation Results with Second Fick's Law.

Diameter	13 mm	16 mm	18 mm
Deff ($m^2 h^{-1}$)	1,19 E-05	1,41 E-05	1,93 E-05
Km Average ($m\ h^{-1}$)	0,006184	0,005628	0,005750

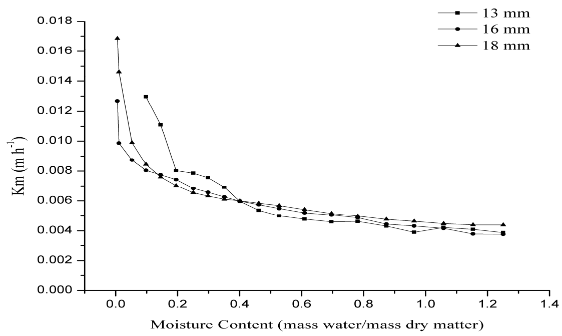

Figure 4: The relationship of convective mass transfer to moisture content in the difference in sample diameter.

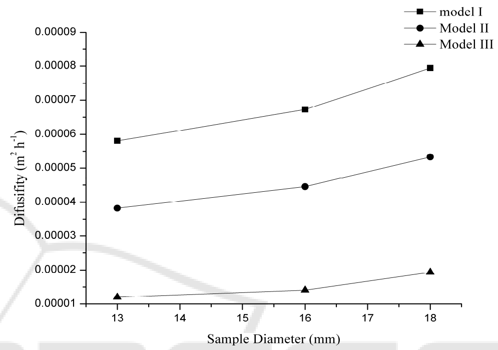

Figure 5: Calculation of humidity diffusivity with several models of sample diameter

3.3 Surface Area Effect on Mass Transfer Parameters

It is known that the diffusivity calculation value of all models increases with increasing sample diameter Figure (5). Increasing the diameter of the sample causes the surface area of the contact area towards mass transfer to be higher, resulting in the diffusivity value of the water molecules increases.

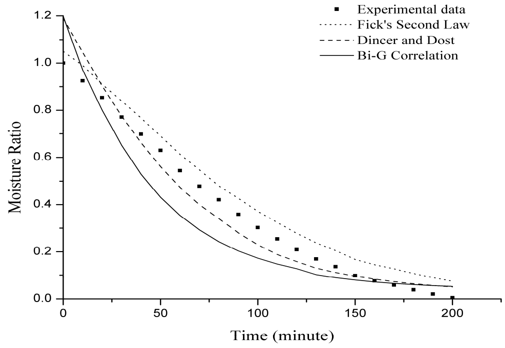

Figure 6: Experimental and predicted dimensionless moisture ratio during oven drying of local biomass at 16 mm diameter

The mass transfer coefficient tends to increase with the sample diameter Table (2 and 3). The mass transfer coefficient is a function of the drying air and the geometry system of the sample. It means the mass transfer process is controlled externally with boundary conditions and not internally controlled. The calculated and experimental moisture ratio profiles for each model are shown in figure (6). It is revealed that for all treatments and predictions by Fick’s Second Law model agreed better with the experimental moisture ratio data in comparison with all model.

4 CONCLUSIONS

In this experiment, wood drying biomass samples were heated in convective mechanism and mathematically-modelled into three different variations. There are three theoretical models in this experiment, Dincer and Dost model, the Bi-G correlation approach and the conventional solution of Fick's second law of diffusion which is used to calculate the mass transfer parameters and predict the dimensionless humidity ratio of the sample drying process. The summaries are listed as follows:

- The entire drying process occurred in a falling rate period and no constant rate period was observed, which indicates diffusion is the dominant physical mechanism that determines the movement of water vapor throughout the sample.
- Biot number values indicate limited simultaneous internal and surface resistance to moisture transfer.
- The mass transfer parameters can be increased by increasing the diameter of the sample (mass diffusion coefficient and moisture transfer coefficient) for larger diameter has a larger contact surface area but contains more moisture content so it requires a longer time.
- From the analysis of those three models, it can be concluded that Fick’s Second Law is the best model to describe the drying process parameters and the mass transfer parameters for Gliricidia sepium in a cylindrical shape because it has minimal error.

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