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Latent Heat of Vaporization of JatiBelanda (*Guazumaulmifolia*) Leaves

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ABSTRACT : One of the coefficients required for calculating energy consumption theoretically in the drying process is the latent heat of vaporization. This coefficient determined from data of equilibrium moisture content (EMC). The objectives of this study were to evaluate a suitable EMC model to predict EMC of jatibelanda leaves and to calculate the latent heat of vaporization of jatibelanda leaves base on EMC data. Experimental data of EMC were fitted by the modified Oswin model, modified Henderson model, modified Halsey model, and modified Chung-Pfost model. These models were evaluated statistically by the coefficient of determination (R2), root square mean errors (RSME), and reduced mean square of deviation (X2). The modified Oswin model fitted reasonably well for predicting the EMC of jatibelanda leaves, and the modified Halsey model was more reasonable for predicting the latent heat of vaporization of jatibelanda leaves. The magnitude of hfg/h ratio of jatibelanda leaves was between 1.189 – 1.919 for moisture content 6 – 18% d.b. The empirical equation as moisture content and temperature function can describe well influence both parameters to values of the latent heat of vaporization of jatiBelanda leaves.

KEYWORDS: drying process, equilibrium moisture content, jatiBelanda leaves, latent heat of vaporization.

I. INTRODUCTION

The available information about bioactive compounds of jatibelanda (GuazumaulmifoliaLamk.) indicates that it has great potential to be used as herbal medicine. Major bioactive compound of jatibelanda leaves are chlorogenic acid (2.53% or 25.3 mg.g-1) and the flavonoid quercetin (2.15% or 21.57 mg.g-1) (Morais et al., 2017). The bioactive compounds in jatibelanda leaves are related to variuos health-beneficial functions including antimicrobial, antioxidant, antiprotozoal, antidiarrheal activities, and cardioprotective effect (Pereira et al., 2019). The main consideration in drying of herbs like jatibelanda leaves is how to preserve of the bioactive compounds which are heat sensitive. Besides, the drying of herbs requires a high amount of energy. In Convective hot-air drying method is commonly used for drying of medicinal herb. Over 85% of industrial dryings are the convective drying with hot air or gases of direct combustion as the drying medium (Mujumdar, 2015). Although in wide use, one of the major disadvantages of convective drying is high energy consumption which is related to the requirement for heating up the drying medium as well as the material (Lechtanska et al., 2015). The energy consumption of convective drying of various leaves has been calculated in specific energy consumption (SEC) by many researchers. SEC of pappermint leaves drying were ranged from 42.721 to 64.712 MJ.kg-1 (Torki-Haechegani et al., 2016), SEC of spearmint leaves drying were ranged from 10.46 to 31.23 MJ.kg-1 (Nozad et al., 2016), and wormwood leaves were varied from 17.64 to 32.09 kWh.kg-1 (Beigi, 2017). The important aspect of the drying processes is energy efficiency. It was calculated based on the heat energy utilized for evaporating water from the sample (Motevali et al., 2016; Hafezi et al., 2015).

The important thermal properties of the products necessary for calculating the energy consumption is latent heat of vaporization for moisture evaporation. This thermal property is often determined by assuming that the evaporation occurs on free water, and the value can be obtained from steam tables (Kaleemullah and Kailappan, 2005). The assumption could be erroneous for calculating energy consumption of low moisture products due to the existence of bound water in the material which requires more energy to evaporate than free water (Purlis, 2019). The latent heat of vaporization of material can be analyzed using the equilibrium moisture content (EMC) data (Tagawa et al., 1993). Equilibrium moisture content is the limit of material moisture content that can be reached in the process of vaporization at a given temperature and relative humidity (Li, 2020). There is a relationship between moisture content of the material and relative humidty of air drying in thermodynamic equilibrium that is known as the sorption isotherms for predicting EMC (Abalone et al., 2006). This information is required for the drying of material that will prevent over-drying and thus decrease drying time, energy costs, mass losses and the risk of quality deterioration (Arabhosseini et al., 2005). Mathematical models of the relationship can be used to predict the equilibrium moisture content (Supakarn et al., 2018). Various EMC models have been studied by researchers, among which were modified Henderson, modified Halsey, modified Chung-Pfost, and modified Oswin (Arabhosseini et al., 2005; George and Cenkowski, 2009; Arabhosseini et al., 2010; Godbolt et al., 2013). Many reseachers have also predicted EMC of various leaves with mathematical models, including tarragon leaves (Arabhosseini et al., 2005), mischantus leaves (Arabhosseini et al., 2010), centellaasiatica leaves (Trirattanapikul and Phuongchandang, 2012), and basil leaves (Lima-Correa et al., 2017). Methods that were used by researchers for determining EMC of leaves are mostly static method. This method usually uses saturated salt solutions to provide constant relative humidities. Static method is more suitable for product storage. Dynamic method requires air flow in its mechanism and this method commonly used in the drying process. The available information on EMC models and the latent heat of vaporization of jatibelanda leaves is very limited in the reported literatures. Therefore, this study was conducted with objectives to evaluate a suitable EMC model for predicting EMC of jatibelanda leaves and to calculate the latent heat of vaporization of jatibelanda leaves base on EMC data.

II. MATERIALS AND METHODS

Jatibelanda leaves were manually harvested at the experimental farm of Tropical Biopharmaca Research Center, IPB University Bogor Indonesia. Before the drying process, samples were cleaned, sorted, and the petiole was cuted. Figure 1 shows the schematic diagram and the laboratory air dryer used in the experiment. It consists of electrical fan, heater, airflow regulator, digital scale, humidifier, microprocessor controller, and drying chamber. A PID (proportional-integral-derivative) controller is used to control air temperature in drying chamber with accuracy of ± 1oC. Air relative humidity is controlled by a PD (proportional-derivative) controller with accuracy of ± 2%. The air velocity was regulated manually by airflow regulator and measured by digital anemometer.

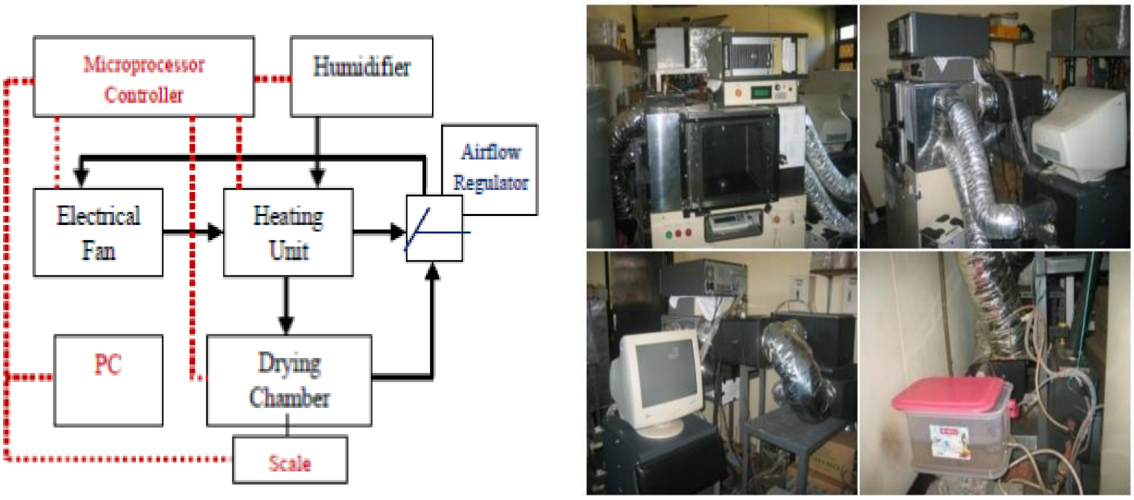

Figure 1. Laboratory air dryer leaves.

Thin layer drying experiments were conducted at a varied drying air temperature (40 oC, 50 oC, and 60 oC) and air relative humidity (0.3, 0.4, 0.5, and 0.6). During drying process, temperature and relative humidity in the drying chamber were automatically controlled and recorded in 5 min intervals. Drying air velocity was kept at 0.5 – 0.6 m.s-1. After the set point was reached (steady-state condition), the jatibelanda leaves were distributed uniformly into the drying tray. The initial mass of jatibelanda leaves were of 15 to 16 g per tray. The drying samples were put on the electronic balance and weighed automatically at 5 min intervals by electronic balance (capacity of 0 – 3100 g and accuracy of 0.01 g) during drying until their weight was constant. The samples weight loss during drying were converted into the moisture content in dry matter basis. The moisture content of samples was measured with hot-air oven set at 105 oC for 12 hours to obtain its bone dry weight. The final moisture content of the samples was considered as EMC. The experiment was repeated three times and the averages of three values were used in data analysis.Mathematical models to describe the relationship between the equilibrium relative humidity, moisture content and temperature that can be used to predict the equilibrium moisture content of jatibelanda leaves are modified Henderson, modified Halsey, modified Chung-Pfost, and modified Oswin. Nonlinear regression analysis was used to fit four models using CurveExpert Professional 2.6.5 software (licensed) for obtaining the model's coefficients

Modified Henderson Model:

$$\mathrm{EMC} = \left(-\frac{1}{\mathrm{A(T+B)}}\ln(1-\mathrm{ERH})\right)^{\frac{1}{\mathrm{C}}} \qquad (1)$$

Modified Oswin Model:

$$\mathrm{EMC} = (\mathrm{A}+\mathrm{BT})\left(\frac{\mathrm{ERH}}{1-\mathrm{ERH}}\right)^{\frac{1}{\mathrm{C}}} \qquad (2)$$

Modified Chung-Pfost Model

$$\mathrm{EMC} = \frac{1}{\mathrm{A}}\ln\left(\ln(\mathrm{ERH})\frac{(\mathrm{B}-\mathrm{T})}{\mathrm{C}}\right) \qquad (3)$$

Modified Halsey Model

$$\mathrm{EMC} = \left(\frac{-\exp(\mathrm{A}+\mathrm{BT})}{\ln(\mathrm{ERH})}\right)^{\frac{1}{\mathrm{C}}} \qquad (4)$$

Where:
EMC - equilibrium moisture content, % d.b
ERH - equilibrium relative humidity, in decimal form
T - temperature, ^{o}C
A, B, dan C - model constant, dimensionless

The three criteria of statistical analysis were used to evaluate the fitness of the experimental data to the models, namely coefficient of determination (R^2), root square mean errors (RMSE), and reduced mean square of deviation(χ^2). The fitness were indicated by highest value of R^2 and lowest value of the χ^2 and RMSE.The latent heat of vaporization is commonly obtained by applying the Clausius-Clapeyron equation to sorption isotherms at different temperature (Manalu et al., 1997; Kaleemullah and Kailappan, 2005), as shown in Eq. (5).

$$\frac{\mathrm{dP}}{\mathrm{dT}} = \frac{\mathrm{h_{fg}}}{(\mathrm{V_v}-\mathrm{V_s})\mathrm{T}} \qquad (5)$$

Where:
P - actual pressure of water vapor, kPa
h_{fg} - latent heat of vaporization, kJ.kg^{-1}
V_v - specific volume of vapor, m$^{3\cdot}$kg^{-1}
V_s - specific volume of liquid, m$^{3\cdot}$kg^{-1}

The relationship between partial pressure of water vapor and the latent heat of vaporization at the same temperature was resulted by integrating the Clausius-Clapeyron equation,considering h_{fg} as a constant value between two given states (Manalu et al., 1997; Silva et al., 2012), as shown in Eq. (6).

$$\frac{\mathrm{h_{fg}}}{\mathrm{h}} = \frac{\ln(\mathrm{p_{v2}})-\ln(\mathrm{p_{v1}})}{\ln(\mathrm{p_{s2}}-\ln(\mathrm{p_{s1}})} \qquad (6)$$

Where:
h - the latent heat of vaporization of free water, kJ.kg^{-1}
p_v - partial pressure of water vapor, kPa
p_s - partial pressure of water vapor at saturation, kPa

The partial pressure of water vapor in jatibelanda leaves at each moisture content was calculated as shown in Eq. (7).

$$\mathrm{p_v} = \mathrm{p_s} \text{ x ERH} \qquad (7)$$

In this study, the equilibrium relative humidity (ERH) of air, will be determined by interpolation of the four matematical EMC models of jatibelanda leaves. Equilibrium relative humidy can be determined for specified values of EMC and T. The partial pressure of water vapor at saturation can be determined using the Eq. (8).

$$p_s = e^{\left[49.20 - 6643/(T+273.15) - 4.522 \ln(T+273.15)\right]} \quad (8)$$

The ratio h_{fg}/h can be determined through Equation 2 that the latent heat of vaporization of free water was determined previuosly using Eq.(9).

$$h = 2503 - 2{,}386\ T \quad (9)$$

The h_{fg}/h ratio was calculated with Eq. 2 for a given EMC in specified temperature. The equilibrium relative humidity of air was calculated through EMC model in two states, namely state 1 with T = T + 1 °C, and state 2 with T = T – 1 °C (Silva et al., 2012). There are two empirical models that was used for predicting h_{fg} in this study. The first, the empiric model was developed by Hall CW (Manalu et al., 1997) as shown in Eq. (10). The second is the empiric model by Silva et al., (2012), was given as shown in Eq. (11).

$$\frac{h_{fg}}{h} = \left(1 + C_1 \exp(-C_2 TM)\right) \quad (10)$$

$$h_{fg} = C_3 M^{(C_4 + C_5 T)} + dT \quad (11)$$

Where:

$C_1, C_2, C_3, C_4, C_5, C_6$ - parameter of fitting

III. RESULTS AND DISCUSSION

The The dynamic method was used to measure EMC in this study. Therefore, the results called as dynamic equilibrium moisture content. It was obtained the best by fitting of the thin layer drying equation to experimental data, which is different from static EMC (Bala, 1997). The relationship between equilibrium moisture content and equilibrium relative humidity of the *jatibelanda* leaves at various temperature (40°C, 50°C, and 60°C) are shown in Fig.2. As it is expected, the decrease in temperature and increase in relative humidity give higher EMC of *jatibelanda* leaves. The driving force for drying is the difference between the vapor pressure of the moisture within the material and the water vapor pressure of the surrounding.

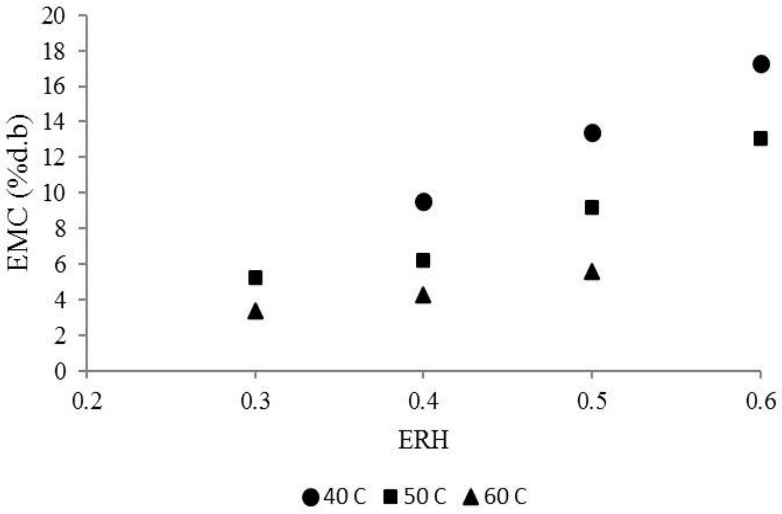

Figure 2. Equilibrium moisture content of *jatibelanda* leaves at different temperatures

The statistical analysis value and the EMC model coefficients are summarized in Table 1. All models gave high coefficient of determination (R^2) values in the range of 0.9537 – 0.9940. The validity of the EMC models was also investigated by comparison of the predicted and measured EMCvalues. Fig. 3 shows the experimental moisture ratio values versus the predicted values by the EMC models for *jatibelanda* leaves. As shown, the predicted EMC are generally banded near to a 45° straight line. This indicates that the EMC models can predict the EMC values of *jatibelanda* leaves appropriately. Among all models, the modified Oswin model obtained the highest value of R^2 and the lowest values of RMSE and χ^2 (*chi-square*) in this study. From Table 1, it was determined that $R^2 = 0.9940$, $\chi^2 = 0.0981$, and RMSE = 0.2621. This model represented the experimental values satisfactorily. The relationship of parameter in modified Oswin model can be shown in Eq. (12). The next best model was the modified Halsey model ($R^2 = 0.9907$, $\chi^2 = 0.1962$. and RMSE = 0.3706).

$$\mathrm{Me} = (27.3085 - 0.3586\,\mathrm{T})\left(\frac{\mathrm{ERH}}{1-\mathrm{ERH}}\right)^{\frac{1}{1.3322}} \qquad 12)$$

Table. 1 Equilibrium moisture content coefficient and summary of statistics

Model	Coefficient values			Statistical parameters		
	A	B	C	R^2	RMSE	χ^2
Modified Henderson	0.0027	-16.6387	0.9277	0.9809	0.5490	0.4306
Modified Oswin	27.3085	-0.3586	1.3322	0.9940	0.2621	0.0981
Modified Chung-Pfost	59.5591	-19.9356	0.1091	0.9537	0.6968	0.6936
Modified Halsey	3.4071	-0.0345	0.9358	0.9907	0.3706	0.1962

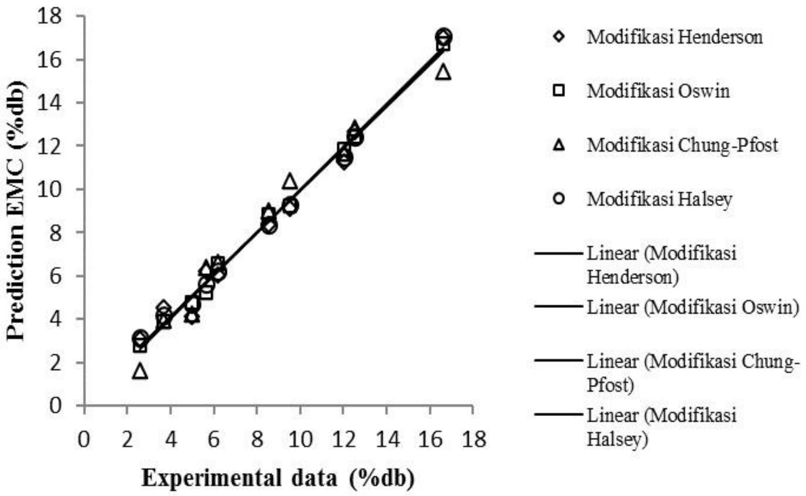

Figure 3. Comparison between experimental and predicted EMC of *jatibelanda* leaves

Arabhosseini et al., (2010) reported that the modified Oswin model was the most suitable for describing the correlation between EMC, ERH and temperature for Mischanthus leaves. This model also can be used to predict the EMC value of corn leaves (Igathinathane et al., 2005). The modified Oswinmodel was a good model for moisture adsorption and desorption of Festucapratensis (Stencl, 2000). The characteristic of material (porosity and bulk density) and physicochemical properties have great influence to resulted EMC values (Kaleemullah and Kailappan, 2005). The modified Oswin model can be used to predict EMC value of *jatibelanda* leaves within a temperature range of 40– 60 ºC and ERH range of 0.3 – 0.6. The modified Oswin model under predict the EMC both at low and high relative humidity condition (Bellur et al., 2009).

Latent heat of vaporization : Base on interpolation of the EMC models, the ERH values at different temperature and constant moisture content can be obtained. Under equilibrium conditions, and assuming that water vapour is an ideal gas, partial pressure of water vapor in Eq. (7) can be determined by multiplying ERH and saturation pressure. Among all models, the modified Halsey model was used to estimate the latent heat of vaporization of *jati belanda* leaves because of reasonable prediction.

The magnitude of h_{fg}/h ratio of *jatibelanda* leaves is between1.189 – 1.919 for moisture content 6 – 18% d.b. Base on Eq. (10), the coefficients in this equation is obtained with fitted used software curve expert professional 2.6.5 with $R^2 = 0.937$. The expression of relationship moisture content, temperature, and h_{fg}/h ratio as shown in Eq.(13).

$$\frac{h_{fg}}{h} = \left(1 + 1.3255\,\exp(-0.00209\,\mathrm{T.M})\right) \qquad 13)$$

According to Eq.(13), the variation of h_{fg}/h ratio of *jatibelanda* leaves is shown in Fig 4, the ratioh_{fg}/h decreases with increase of temperature while increases with the decrease of moisture content. The influence of moisture content is greater than temperature to h_{fg}/h ratio.The magnitude of h_{fg}/h ratio was varied widely between some agricultural products. The highest h_{fg}/h among tested crops and foods is between 1.35 – 1.5 for moisture content 11 – 16% d.b (Cenkowski et al., 1992). The h_{fg}/h ratio of bananas is ranged 1.0371 – 1.0913 for moisture content 10 – 30% d.b (Silva et al., 2012) and red chillies is ranged 1.0023 – 1.3421 for moisture content 5 – 400% d.b (Kaleemullah and Kailappan, 2005).

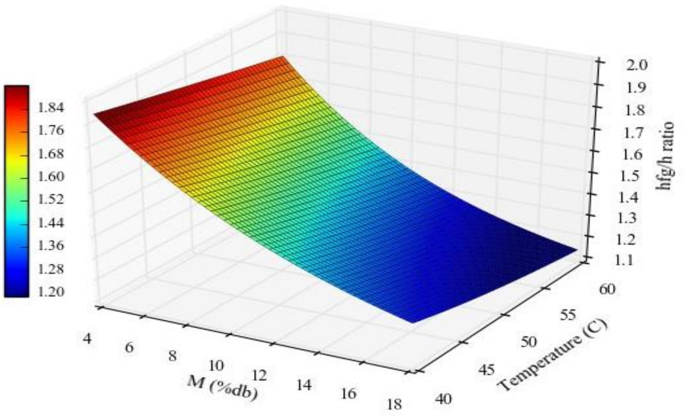

Figure4.Relationship of moisture content and temperature to h_{fg}/h ratio

The four parameters in Eq.(14) were determined by curve fitting in this study. The coefficient of determination of nonlinear regression was obtained as follows R^2 = 0.9879. This equation that was recommended by Silva et al., (2012) can be considered as option for determination of the latent heat of vaporization of *jatibelanda* leaves for moisture content 6 – 18% d.b.

$$h_{fg} = 7.495.10^3 M^{(0.245-0.018T)} + 36.442T \tag{14}$$

Base on Eq.(14), the profile of latent heat of vaporization of *jatibelanda* leaves with temperature and moisture content are shown in Fig 5. The latent heat of vaporization decreases with increase temperature and moisture content of material (Abalone et al., 2006; Li, 2020). This shows that the energy consumption to evaporate water is greater at lower temperature and moisture content (Manalu et al., 1997). At lower moisture content (under 10% d.b), the influence of moisture content on the latent heat of vaporization of *jatibelanda* leaves is as significant as the influence of temperature as can be seen in Fig 5. The latent heat of vaporization of *jatibelanda* leaves increases non-linearly. The lower moisture content, a significant amount of the water is bound (Li, 2020). At lower moisture level, the strength of water binding is increase. The lower moisture content increases the amount of energy required to remove moisture from material, in part due to the greater resistance to moisture movement from internal to surface of the material (Cenkowski et al., 1992).

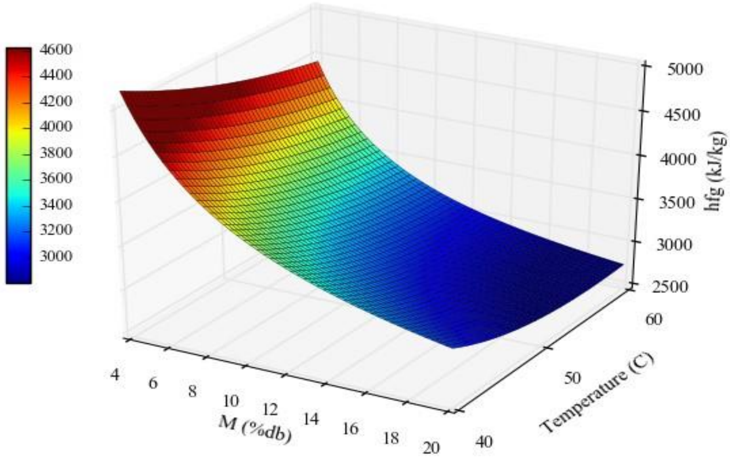

Figure5. Variation of the latent heat of vaporization in *jati belanda* leaves

The laten heat of vaporozation of free water is not significanly different from the latent heat of vaporization of moisture from celery leaves for moisture content above 10% d.b and above 15% d.b for chamomile tea (Cenkowski et al., 1992). The increase mositure content causes the latent heat of vaporization of jati belanda leaves toward asymtotic value of free water. The moisture inside product behaved almost like free water for higher moisture content.Hence, it seems reasonable to assume that the latent heat of vaporization of product is equal to that of free water (Tagawa et al., 1993; Kaleemullah and Kailappan, 2005).

IV. CONCLUSION

The modified Oswin model showed the best fit for predicting equilibrium moisture content of jatibelanda leaves with R2 = 0.9940, $\chi 2$ = 0.0981, and RMSE = 0.2621. Empirical equation for estimating hfg/h ratio and hfg as moisture content and temperature function can be used to predict the latent heat of vaporization of jatibelanda for moisture content 6 – 18% d.b. The energy required to vaporise water from jatibelanda leaves is dependent upon its moisture content and temperature.

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