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The effect of air flow rate on single-layer drying characteristics of *Arabica* coffee

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Abstract

This study was intended to evaluate the behavior of Arabica Coffee (*Coffea arabica* L.) bean during the single-layer drying process under several levels of drying air velocity. The research was carried out at the Processing Laboratory of Agricultural Engineering Department, Hasanuddin University - Indonesia, during the period of February to May 2011. Sample used was an Arabica Coffee, Line S-795 variety, obtained from a coffee farmer in Enrekang Regency - South Sulawesi. The main equipment applied was a tray dryer, Model EH-TD-300 Eunha Fluid Science. The dryer was constructed to flow the drying-air parallel with the crop-layer. Three different levels of air velocity (0.5, 1.2, and 1.8 m/s) under constant drying temperature of 47°C were exercised in this research. The moisture ratio was determined for each drying run and fitted to several existing thin-layer drying models. Research results indicated that among the models, Hii *et al.* model (2008) is the best one, R^2 reached up to 0.99, to represent the behavior of the Arabica Coffee during the single-layer drying process. It was also observed that increasing air velocity from 0.5 m/s to 1.8 m/s failed to considerably improve the drying rate, although the paired t-test indicated that their moisture ratios were statistically different. The curves of the moisture contents (dry-basis) resulting from the three levels of air velocity across elapsed drying time were very much overlapping, especially at the elapsed drying time greater than 10 hours.

Introduction

Coffee is one of the primary estate crops in Indonesia. South Sulawesi Province has been known as a coffee production center. South Sulawesi - Central Bureau of Statistics (2009) reported that this province produced about 4 thousands ton of Robusta Coffee and around 18 thousands ton of Arabica Coffee in 2008. These production levels were just about the same with those in 2007. The contribution of Arabica Coffee to the export value of South Sulawesi was very significant as well, around US$ 19 million in 2008.

Drying process is a major step in coffee processing. This step is crucial since it will dictate the performance of coffee beans at least during the storage time. GTZ-PPP Project (2002) reported that coffee beans have to be dried down to a safe moisture content level, at least 11-12%. Mould development will be minimized at this level. It is also reported that breakage during the hulling process will also decrease under this level of moisture content.

Studies focusing on the coffee behavior during the drying process have been reported by several researchers. Among others, Corrêa *et al.* (2006) studied the drying characteristics and kinetics of coffee berry under the drying temperatures of 40°, 50° and 60°C. Corrêa *et al.* (2010) also observed the moisture sorption isotherms and isosteric heat of sorption of coffee in different processing levels. Coradi *et al.* (2007) tried to determine the effect of drying and storage conditions on the quality of natural and washed coffee. This research emphasized the importance of the adequate storage besides the correct drying process to preserve coffee's qualities. Ciro-Velásquez *et al*. (2010) conducted a numerical simulation of thin-layer coffee drying by control volumes. Similar to Corrêa *et al.* (2006), this simulation also used drying air temperatures of 40°, 50° and 60°C.

Most of the above mentioned studies applied one level of drying air velocity under several different levels of drying temperature. On the contrary, this research was designed to apply a constant drying temperature of 47°C with three different levels of air velocity (0.5, 1.2, and 1.8 m/s). With this arrangement, it would provide a good perspective on how moisture contents of coffee bean behaved when drying air velocity was increased. The selected drying temperature was in the range of the recommended level by GTZ-PPP Project (2002), between 45 to

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55°C. Similarly, the air velocities used (0.5, 1.2 and 1.8 m/s) were also considered to be reasonable since they were in the range of those commonly exercised by several researchers during the study of the thin-layer drying process. Coradi *et al.* (2007) applied drying air velocity of about 0.3 m/s in their research. Ibrahim *et al.* (2009) observed the drying kinetics of lemon grass under a fixed air velocity of 1.0 m/s. Chinenye *et al*. (2010) used an air velocity of 2.5 m/s during the study of cocoa bean drying kinetics.

The main objective of this research was to find-out the best thin-layer drying model to represent the behavior of the moisture contents of the Arabica Coffee, specifically for Line S-795 variety, under several levels of drying air velocity.

Materials and Method

Coffee Arabica sample source

Sample used was an Arabica Coffee, Line S-795 variety, obtained from a coffee farmer in Enrekang Regency (about 235 km to the north of Makassar city) - South Sulawesi, Indonesia. Fresh coffee fruits from the farmer were processed (peeled and fermented for about 24 hours) to get fresh coffee beans. To obtain the best quality beans, only red fruits were used in the experiment.

Main equipment

The main equipment applied was a tray dryer, Model EH-TD-300 Eunha Fluid Science. The dryer was constructed to flow the drying-air parallel with the crop-layer. It is also equipped with a pair of dry and wet bulb thermometers to facilitate an easy assessment on the drying air temperature and relative humidity. The schematic diagram of this dryer was depicted in Figure 1. A portable digital anemometer (0.1 m/s accuracy) was used to calibrate drying air velocity. The drying air velocity was measured on the air outlet of the dryer. To measure the sub-sample weight across drying time, a digital balance with an accuracy of 0.001 g placed close to the dryer was utilized.

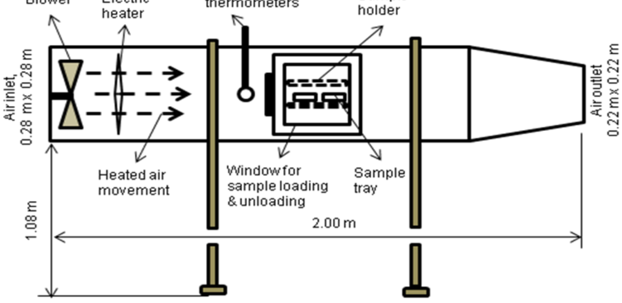

Figure 1. Schematic diagram of the tray dryer used in the experiment

Experimental procedure

The experiment was carried out at the Processing Laboratory of Agricultural Engineering Department, Hasanuddin University - Indonesia, during the period of February to May 2011. Three different levels of air velocity (0.5, 1.2, and 1.8 m/s) under constant drying temperature of 47°C were exercised in this research. The sample, for each drying run, was divided into two sub samples using two sample trays to increase the accuracy of the measurement. The weight of each sub-sample was around 100 g. The drying temperature and air velocity were stabilized for about one hour before the two sub-samples were loaded into the drying chamber. The initial weight of each sub-sample was recorded prior to the loading process. The weight of the sub-sample was then recorded for every hour elapsed drying time. The sub-sample was unloaded from the drying chamber any time the weighing process was performed. The drying process was terminated when the weight of the sub-samples had achieved a constant value for about 3 hours. It was assumed that at this point time the sample weight was in an equilibrium stage. The sub-samples were then oven-dried to get their dry weight. The dry-basis moisture contents (Mc_{db}) of the sub-sample across elapsed drying time were calculated for each drying air velocity. The average moisture content of the two sub-samples was calculated and designated as the calculated Mc_{db}.

Model performance evaluation

All calculated Mc_{db} were transformed into moisture ratio for elapse drying time ($MR_{(t)}$) using the following formula:

$$MR_{(t)} = \frac{Mc_{db(t)} - Me}{Mo - Me}$$

Where :
Mo = Initial Mc_{db} (% dry basis)
$Mc_{db(t)}$ = Mc_{db} at elapsed drying time t (% dry basis)
Me = Equilibrium moisture content (% dry basis) using the final Mc_{db} of each drying run.

The characteristics of the moisture ratio across the drying time were then fitted to the thin layer drying models depicted in Table 1. The models were used by Muhidong *et al.* (1992), Corrêa *et al.* (2006), Kingsly *et al*. (2007), Yadollahinia *et al.* (2008), Hii *et al.* (2008), Ibrahim *et al.* (2009), Meisami-asl *et al.* (2009), and Muhidong (2011).

The value of each drying constant was determined using the Microsoft Excel Solver. The initial step of the analysis was to define the names of all drying constants involved in the model and set their initial values. The initial predicted values of the $MR_{(t)}$ were then calculated according to the model being

Table 1. Thin-layer drying models tested in this research

No	Model Name	Equation	References
1	Newton	MR = exp(-a.t)	Muhidong *et al.* (2011)
2	Henderson and Pabis	MR = a.exp(-b.t)	Ibrahim *et al.* (2009)
3	Page	MR = exp(-a.t^b)	Corrêa *et al.* (2006)
4	Modified Page	MR = exp(-$(a.t)^b$)	Kingsly *et al.* (2007)
5	Two term model	MR = a.exp(-b.t) + k.exp(-d.t)	Meisami-asl *et al.* (2009)
6	Verma *et al.*	MR = a.exp(-b.t) + (1-a).exp(-k.t)	Hii *et al.* (2008)
7	Diffusion approach	MR = a.exp(-b.t) + (1-a).exp(-b.k.t)	Yadollahinia *et al.* (2008)
8	Hii *et al.*	MR = a.exp(-b.t^k)+ d.exp(-e.t^k)	Hii *et al.* (2008)

Where t represents elapse drying time (in hour) and a, b, k, d, and e are drying constant.

evaluated. With this information, the total quadratic-difference between the predicted and observed $MR_{(t)}$ values was computed. The Solver was then utilized to minimize such total difference by automatically adjusting the values of the defined drying constants. The values of the drying constants obtained at this stage were finally set as the true values of the drying constants of the related model. Hii *et al.* (2008) also used the Microsoft Excel Solver to support their analysis. The best fitted model was selected based on its R^2 value, Chi-squared (χ^2), and the Root Mean Squared Error (RMSE). R^2 value was computed using the RSQ function of the Microsoft Excel. As Mohammadi *et al.* (2008), the following methods were applied to resolve Chi-squared (χ^2) and RMSE values:

$$X^2 = \frac{\sum(MR_{(observed)} - MR_{(predicted)})}{N-n}$$

$$RMSE = \frac{\sqrt{\sum(MR_{(observed)} - MR_{(predicted)})^2}}{N}$$

Where N symbolizes the number of observations and n is the number of parameters involved in the model. A model with the highest R^2 and at the same time producing the smallest χ^2 and RMSE values would be considered as the best fitted model to represent the behavior of the Arabica Coffee during the single-layer drying process at the given drying temperature and air velocities.

Results and Discussion

This study found that the initial moisture content (Mo) of the sample was about 52% wet basis or about 105% dry basis. The equilibrium moisture content (Me) which was set equal to the moisture content at the final stage of the drying process was about 8.4% wet basis or around 8.7% dry basis. These Mo and Me values along with the moisture content value observed at each elapsed drying time were used to determine the moisture ratios, $MR_{(observed)}$.

The behavior of $MR_{(observed)}$ across the elapsed drying time was displayed in Figure 2. This figure, however, could not clearly visualize the behavior differences among the three drying conditions. The curves of $MR_{(observed)}$ resulting from the three levels of air velocity across elapsed drying time were very much overlapping, especially at the elapsed drying time greater than 10 hours. This phenomenon indicated that increasing drying air velocity from 0.5 m/s to 1.8 m/s was not effective enough in boosting the drying rate of Arabica Coffee beans.

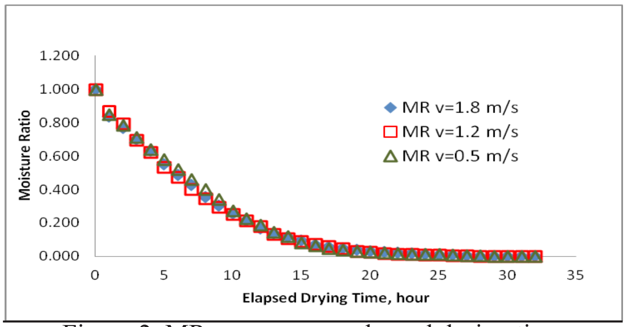

Figure 2. $MR_{(observed)}$ across elapsed drying time

A paired t-test was then utilized to check the differences. The test results truly designated that $MR_{(observed)}$ resulted from the drying air velocities of 1.8 m/s and 1.2 m/s are not significantly different, p-value of 0.232. Nonetheless, these two velocities are indeed significantly different from the 0.5 m/s drying air velocity, p-values of less than 0.01. With such results, it was decided to take the average $MR_{(observed)}$ values of the two drying air velocities, 1.8 m/s and 1.2 m/s. Consequently, the number of data sets was reduced from three to two. The best model to represent the thin-layer drying process was then evaluated based on the behaviors of the two data sets.

All mathematical models shown in Table 1 were assessed their performances when fitting to the two data sets generated above. The Microsoft Excel Solver was used to search out the values of the parameters involved in each model. In addition, The R^2, Chi-squared (χ^2), and RMSE values were also calculated. The result summary of the assessment is provided in Table 2. Table 2 strongly indicated that Hii *et al.* model (2008) has the best performances compared to the other models. Hii *et al.* model (2008) offered the highest R^2 values with the lowest Chi-squared (χ^2) and RMSE. The performance of this model was graphically exposed in Figures 3 and 4. The second and the third best models were demonstrated by the Diffusion Approach and Page/Modified Page models, respectively. These results are different from the findings of Corrêa *et al.* (2006) where Page and Verna *et al.* models are found to be the best models to represent the behavior of the coffee berry during

Table 2. Values of parameters involved in the models being evaluated along with the values of R^2, χ^2, and RMSE

#	Model Name	Drying Air Velocity	a	b	k	d	e	R^2	χ^2	*RMSE*
1	Newton	1.8 and 1.2 m/s	0.139208					0.994467	0.000842	0.028561
2	Henderson and Pabis		1.036595	0.143897				0.993265	0.000762	0.026724
3	Page		0.092933	1.182864				0.997497	0.000256	0.015486
4	Modified Page		0.134179	1.182869				0.997497	0.000256	0.015486
5	Two term model		0.518298	0.143897	0.518298	0.143897		0.993265	0.000816	0.026724
6	Verma *et. al.*		0.137107	0.139208	0.139208			0.994467	0.0009	0.028561
7	Diffusion approach		-13.7082	0.228686	0.960331			0.997964	0.000215	0.013943
8	Hii, *et al.*		0.479113	0.074974	1.260058	0.479113	0.074974	0.998148	0.000193	0.012768
						Max R^2, Min χ^2, Min RMSE		0.998148	0.000193	0.012768
#	**Model Name**	**Drying Air Velocity**	**a**	**b**	**k**	**d**	**e**	**R^2**	**χ^2**	***RMSE***
1	Newton	0.5 m/s	0.132216					0.988211	0.001658	0.040082
2	Henderson and Pabis		1.045126	0.137602				0.986331	0.001541	0.038007
3	Page		0.074848	1.251377				0.994175	0.000614	0.023996
4	Modified Page		0.12599	1.251377				0.994175	0.000614	0.023996
5	Two term model		0.522563	0.137602	0.522563	0.137602		0.986331	0.001651	0.038007
6	Verma *et. al.*		0.234426	0.132216	0.132216			0.988211	0.001773	0.040082
7	Diffusion approach		-5.48818	0.237598	0.895321			0.994359	0.000602	0.023354
8	Hii, *et al.*		0.467429	0.050137	1.396971	0.467429	0.050137	0.995762	0.000449	0.019466
						Max R^2, Min χ^2, Min RMSE		0.995762	0.000449	0.019466

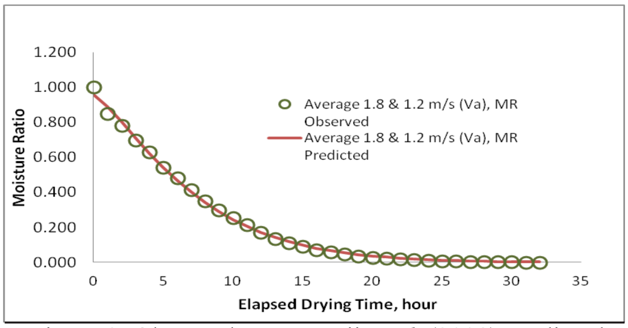

Figure 3. Observed MR vs. Hii *et al.* (2008) predicted values for drying air velocities of 1.8 m/s and 1.2 m/s.

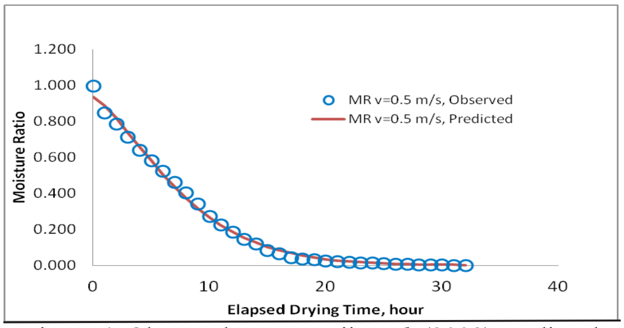

Figure 4. Observed MR vs. Hii *et al.* (2008) predicted values for drying air velocity of 0.5 m/s.

the thin-layer drying process. However, it should be noticed that Corrêa *et al.* (2006) study did not include Hii *et al.* model (2008) in their model evaluations.

Conclusions

This study concluded that among the models tested, Hii *et al.* model (2008) has the best performance, R^2 reached up to 0.998, to represent the behavior of the Arabica Coffee beans during the single-layer drying process. It was also observed that increasing air velocity from 0.5 m/s to 1.8 m/s failed to considerably improve the drying rate, although the paired t-test indicated that their moisture ratios were statistically different. The curves of the moisture contents (dry-basis) resulting from the three levels of air velocity across elapsed drying time were very much overlapping, especially at the elapsed drying time greater than 10 hours.

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