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Procedia Environmental Sciences 23 (2015) 2 – 10
Procedia Environmental Sciences

International Conference on Tropical and Coastal Region Eco-Development 2014(ICTCRED 2014)

Low Temperature Seaweed Drying Using Dehumidified Air

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Abstract

The seaweeds are the important commodities as raw material for food or additives. One of the popular seaweeds, *Eucheuma cottonii*, contains carrageenan for starch or fiber sources that can be applied for beverages or gelatin. Currently, the seaweed has been widely provided as dry product in order to minimize the cost for transportation as well as prolong storage life. However, current drying process still deals with energy in-efficiency and product quality degradation. The dehumidified air can be an option to retain the seaweed quality. With lower humidity, the driving force for drying can be improved in which shortened drying time. This research aimed to study the effect of air temperature, humidity, and velocity on seaweed drying. For supporting the study, the several drying kinetic models were developed to predict drying rate. Furthermore, the seaweed quality was evaluated based on rehydration ratio. Results showed that for all cases, drying at 70°C or below can provide reasonable drying time. The higher air temperature and air flow, the faster drying time. Meanwhile, the dehumidified air also affected drying time positively. In addition, the model based on Page is the best option to estimate the drying rate. For all drying condition, the rehydration ratio of dry seaweed was close to the initial wet condition. This implied that the dry seaweed was very suitable for food.

Peer-review under responsibility of scientific committee of the ICTCRED 2014

Keywords: Euchema cottonii; humidity, kinetic, seaweed

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Peer-review under responsibility of scientific committee of the ICTCRED 2014
doi:10.1016/j.proenv.2015.01.002

Nomenclature

X	the moisture content in product
X_e	the equilibrium moisture
X_0	initial moisture content
MR	Moisture ratio
B	the constant of sorption
D	the constant of sorption
a_w	water activity
K	the constant of sorption
L	the material thickness
D_{eff}	Effective diffusivity
t	sampling time
k	constant of drying
μ_k	kinematic viscosity

1. Introduction

The seaweed is the important product in food as natural fiber resources. It has been also used as raw material for food additive such carrageenan, alginate, and agar. Harvested seaweed containing about 90% water required to be dried before distributing to the markets or consumers. Currently, two types of seaweed drying have been applied, namely direct sunlight dryer and conventional convective dryer. The direct sunlight dryer was very simple and cheap. However, the dry product quality and process continuity depend on climate or weather. Moreover, by placing in the opened area, the dry seaweed product was not hygiene[1,2]. The conventional convective dryer was more convenience for flexibility drying condition and ensure the process continuity. However, the cost for energy and nutrition degradation due to the heat introduction, became the main problems[1,2].

Refer to material and equipment, the several seaweed dryers have been studied. Tello-Ireland et al., (2011) studied the effect of hot air drying on *Gracilaria chilensis*[3]. The result showed the higher temperature reduced the seaweed re-hydration and antioxidant activity. It mean that the higher temperature was not recommended. Gupta et al., (2011), stated that drying kinetic of seaweed can be predicted[4]. The moisture diffusion depend on temperature following Arrhenius relationship[4]. They also found that phytochemicals substance decreased during the drying process.

Fudholi et al., (2011) studied the effects of air temperature and humidity on the drying time and kinetics of seaweed[5]. The research concluded that higher temperature, faster drying rate. Several models were also validated to express the drying curve where the Page model can represent the drying curve precisely. The research was continued to design seaweed drying by solar dryer[6]. Results also showed that the Page model was still valid. The drying time was about 7 hours to dry seaweed from 94.60% up to 8.33%. Mohamed et al., (2007) has investigated the effect of air temperature and flow on the drying kinetic of *Gelidium sesquipedale*[7]. Two term models were formulated in which showed the good model prediction.

The seaweed contains heat sensitive material such as protein, and starch. The operational temperature and drying time are key factor to retain seaweed quality. Higher temperature can speed up drying time [1]. However, the nutrition such as protein will deteriorate. Meanwhile, too long drying time also increased the total of nutrition degradation. Based on the above references, the predicted drying time at several operational temperature was still the important issue. Hence, the drying process can be shorter and the product quality can be higher.

Adsorption dryer with zeolite can be an option for seaweed drying. In this case, the air as drying medium was contacted with zeolite to remove the water content (air dehumidification). With low relative humidity, the driving force for drying can be enhanced [8,9]. So, the seaweed drying can be well conducted in low temperature and the product quality can be retained.

This paper discusses the drying time for seaweed at various temperature, air flow, and humidity. In doing so, several standard kinetic models for drying were also validated using experiment result. As indicators, the drying time was estimated, and product quality in term of rehydration capacity was observed.

2. Research Method

2.1 Experiment Set up

Fig. 1 showed main equipment on this study. Seaweed drying used tray dryer completed with blower to supply air and heater (HE-01) to adjust air temperature with accuracy 1°C. The air temperature and humidity were measured by KW0600561, Krisbow®, Indonesia (noted as T-RH). The air velocity was measured with an anemometer KW0600562, Krisbow ®, Indonesia (noted as F1)[1].

The ambient air with 70 – 80% relative humidity (RH), and 29 - 33°C passed the adsorber column (suppose A) which contains zeolite 3A (provided by Zeochem, Switzerland). About 80 - 90% of water in air was removed, and the air temperature increased 5 - 10°C due to the adsorption heat. The dehumidified air was then heated in HE-01. The hot air was fed to the dryer to dry the seaweed (*Eucheuma cottonii*) with initial water content about 90%. Every 30 minutes, the water content in the seaweed was measured by gravimetry. After 60 minutes, the zeolite in column A was saturated. The air dehumidification was moved to column B. While, zeolite in column A was regenerated. The process was stopped for 150 minutes. The data in the form of moisture content versus time was plotted in graph and used for model validation. While the proximate contents (protein, amylose) were analyzed after the drying. In addition, the physical properties of seaweed namely rehydration ratio was evaluated. The procedure was applied for air temperature 40, 50, 60, and 70°C and velocity (5.0 and 7.0 m.s^{-1}).

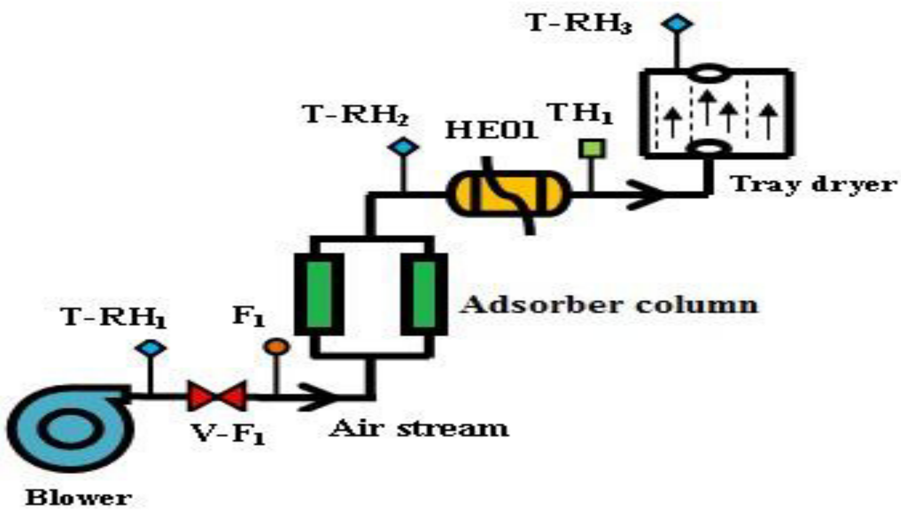

Fig. 1. The schematic of tray dryer with air dehumidifier system

2.2. Model Development

Eucheuma cottonii was put on tray, see Fig. 2. The air was homogeneously distributed through the bottom of dryer. Then, it flew to the top of dryer and contacted with the product. The sensible heat was transferred from the air to the product. The water evaporated from the surface of product. While, remain water diffused from inside to the surface driven by moisture content different. The water removal, was estimated by observing the moisture ratio (MR) calculated by equation 1, as follows:[1]

$$MR = \frac{X - X_e}{X_0 - X_e} \quad (1)$$

Where X is the moisture content at sampling time (gr water/gr dry seaweed), X_e the equilibrium moisture content (gr water/gr dry seaweed), and X_0 is the initial moisture content, (gr water/gr dry seaweed).

The MR versus time for all drying conditions were used for validating constant of drying kinetic in three standard models, as presented in Table 1. The equilibrium moisture content (X_e) was given by GAB equation, as presented in equation 2[1,10].

$$X_e = \frac{B\,D\,K\,a_w}{(1 - K\,a_w)(1 - K\,a_w + B\,K\,a_w)} \tag{2}$$

With B, D, K the GAB constant for carrageenan[1,10], a_w is the water activity which is assumed to be equivalent to relative humidity. Constants of B, D and K were 23.330; 0.114; and 0.854, respectively. The constant were also proportionally modified based on the temperature change. In thi case, the soprtion of carrageenan was assumed similar with *Eucheuma cottonii*. Then, the constant of GAB equation can be adopted and the value of equilibrium moisture can be estimated.

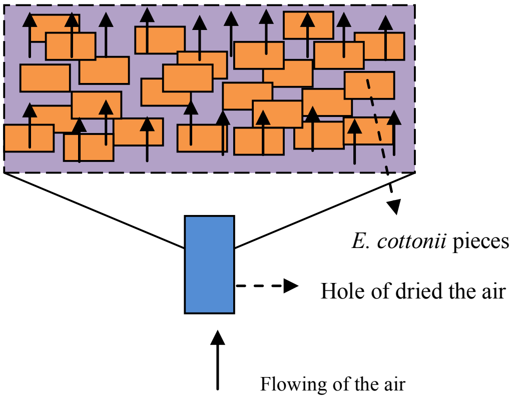

Fig. 2. The illustration of the air on drying *Eucheuma cottonii*

Table 1. Kinetic model for seaweed drying[5]

Model Name	Equation
Newton	MR = exp (-kt)
Page	MR = exp (-kt^n)
Henderson & Pabis	MR = a. exp (-kt)

The mass transfer can be estimated by the effective diffusivity, D_{eff}, (see equation 3), with the following assumptions[1].

1. The value of the effective diffusivity is constant
2. Shrinkage of sample is neglected

$$\ln MR = \ln\left(\frac{8}{\pi^2}\right) - \frac{\pi^2 \times D_{eff} \times t}{4L^2} \tag{3}$$

The L is the average thickness of material, (m), D_{eff} is the moisture diffusivity ($m^2.s^{-1}$), t is sampling time (second). The Sherwood number (Sh) is mass transfer coefficient which including air velocity in tray dryer. Sh was function of Reynold number (Re), and Schmid number (Sc) referred to the following equation[1] :

$$Sh = 0{,}3 + \left(\frac{0{,}62 N_{Re}^{1/2} Sc^{1/3}}{1+\left\{\left(\frac{0{,}4}{Sc}\right)^{2/3}\right\}^{1/4}}\right)\left[1+\left\{\left(\frac{N_{Re}}{282000}\right)^{5/8}\right\}\right]^{4/5} \tag{4}$$

$$Sc = \frac{\mu_k}{D_{eff}} \tag{5}$$

Where μ_k = kinematic viscosity, $m^2.s^{-1}$. The drying time can be predicted. For example with Newton equation, the drying time was estimated as follows:

$$MR = \exp(-kt) \tag{6}$$

$$t = -\frac{\ln MR}{k} \tag{7}$$

Here, t = drying time, (second), and k = constant drying rate, (s^{-1}). The values were then converted to minute. The procedure was repeated for Page and Henderson & Pabis models as depicted in Table 1.

3. Result and Discussion

The seaweed drying was observed at different operational temperature, air velocity, with and without zeolite. The moisture content versus time was illustrated in graph. Next, the drying rate, and the drying time were predicted with models. Moreover, the quality product was analyzed based on rehydration capacity value.

3.1 The effect of zeolite

Seaweed drying at 50°C and 60°C and air velocity 5.0 $m.s^{-1}$ was depicted in Fig. 3. Based on the results, drying with zeolite can give the positive effect on water content removal. However, the air dehumidification effect was not significant for temperature 60°C. It can indicated that the change of water removal during sampling time was slight different, only. The result also showed that the increase air temperature can speed up water removal. With higher temperature, the water diffusivity increased[1,11]. Therefore, more water moved from inside to the surface of seaweed.

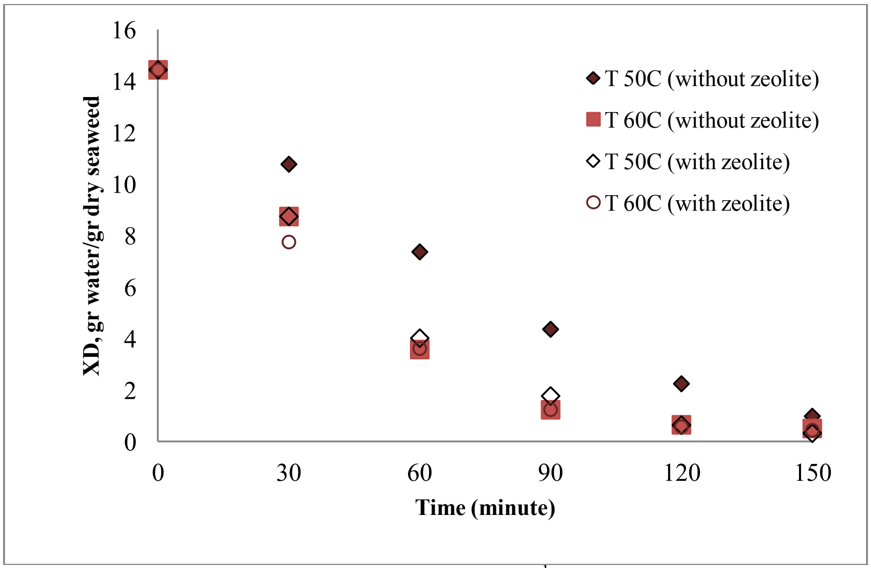

Fig. 3. Seaweed drying with and without zeolite at 5.0 $m.s^{-1}$ (for 50°C (T 50C) and 60°C(T 60C))

3.2 The effect of operational temperature

The seaweed drying was repeated for zeolite application at operational temperature 40 - 70°C and air velocity 5.0 $m.s^{-1}$. The moisture content was observed every 30 minutes (Fig. 4). Using this result, the kinetic of drying as well as drying time were estimated. As previously pointed, the water removal increased with the increase of temperature (see Fig. 4 and Fig. 3). At higher temperature, the water movement from inside to the surface of seaweed increased. Then, the water evaporation can be higher[1,3,5,11].

The water diffusivity, drying rate and drying time were estimated using equation 1 – 7. The drying rate of *Eucheuma cottonii* ranged 10^{-3} – 10^{-2} $minute^{-1}$ with effective moisture diffusivity $1.7x10^{-8}$ – $1.2x10^{-7}$ $m^2.s^{-2}$. The values still comparable with provious research[1]. The drying rate was estimated using 3 models (newton, Page, Henderson & Pabis) as depicted in Table 2. Based on sum of square error (SSE) value, Page model was the most favorable, as pointed in previous research[5]. The Page model and experiment results were depicted in Fig. 5.

Eucheuma cottonii contained nutrition such as protein, fat, amylose, and amylopection. The nutrition were very sensitive with the change of air temperature[3, 4]. The nutrition degradation can be known with the change of texture represented by rehydration capacity. Rehydration capacity was the ability of dry material to adsorb and form linkage with water. Before drying, the water content in the seaweed (*Eucheuma cottonii*) was about 90 - 95% (wet basis or 9

– 19 gr water/gr dry seaweed). After drying process, the rehydration capacity value was given in Table 3. Based on this observation, seaweed drying at 40 – 70°C, did not degrade the texture[1,2,11]. The rehydration capacity ranged 11.9 up to 13.6 were still comparable with the initial value.

Table 2. Constant of drying kinetic at 5.0 m.s^{-1} with air dehumidification by zeolite

Temperature	k, x 10^{-3} minute^{-1}					Sum of square error (SSE)x10^{-5}		
°C	Newton	Page	n	Henderson & Pabis	a	Newton	Page	Henderson & Pabis
40	6.52	4.14	1.09	6.73	1.02	0.80	0.01	0.99
50	26.52	5.66	1.32	28.79	1.28	1.20	0.11	1.58
60	26.16	12.66	1.16	26.67	1.06	0.09	0.05	0.02
70	35.63	21.82	1.11	36.03	1.05	5.41	0.02	5.90

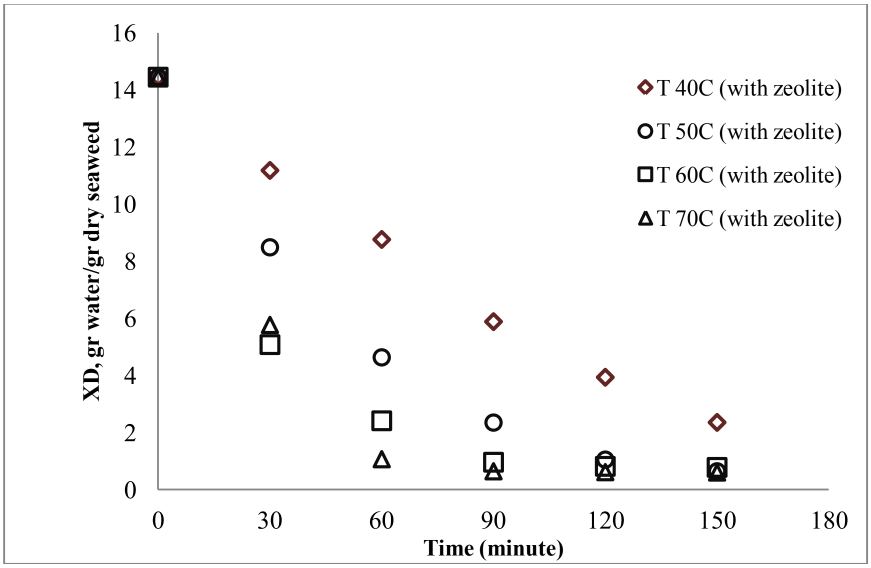

Fig. 4. **S**eaweed drying with zeolite at 5.0 m.s^{-1} (for 40°C (T40C), 50°C (T50C), 60°C(T60C) and 70°C (T 70C))

Table 3. Rehydration capacity of seaweed under various drying temperature

Temperature °C	Rehydration capacity (gr water/gr dry seaweed)
40	11.9
50	12.6
60	12.6
70	13.6

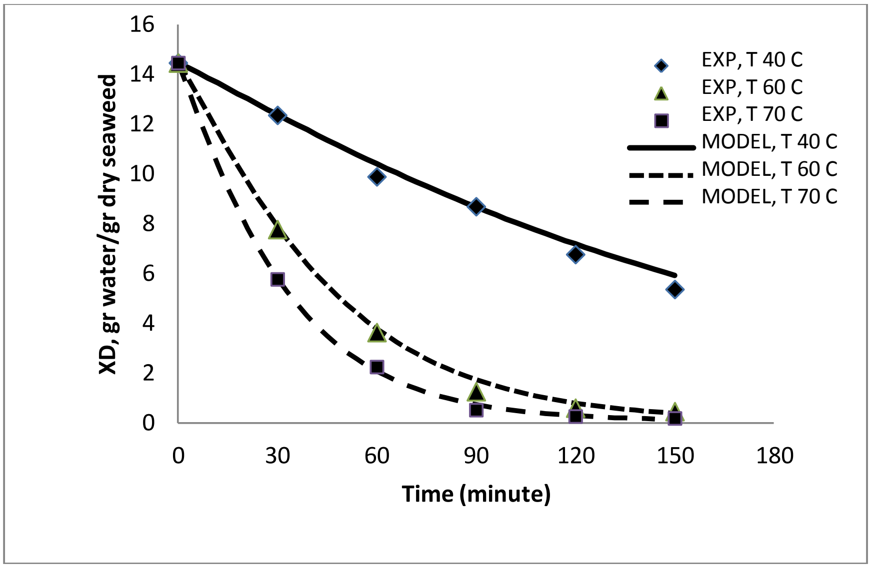

Fig. 5. The fitting experiment and Page model at 5.0 m.s^{-1} (for 40°C (T40C), 60°C (T50C), & 70°C (T 70C))

3.3 The effect of air velocity

The air velocity were applied at 5.0 and 7.0 m.s^{-1} for air dehumidification with zeolite. The air velocity change the Sherwood and Reynold number. Higher velocity resulted greater Reynold and Reynold number (equation 4 and 5). Thus, the constant of drying kinetic increased (see Table 4). With faster drying rate, the time for drying can be shorter[1,5,6].

Table 4. Constant of drying kinetic at 50°C with air dehumidification by zeolite

velocity m.s^{-1}	k, x 10^{-3} minute^{-1}					Sum of square error (SSE)x10^{-5}		
	Newton	Page	n	Henderson & Pabis	a	Newton	Page	Henderson & Pabis
5.0	26.52	5.66	1.32	28.79	1.28	1.20	0.11	1.58
7.0	27.76	6.89	1.15	36.03	1.11	0.64	0.14	0.75

3.4 Drying time estimation

The drying time can be predicted by Page model at various relative humidity and temperature. The drying time was estimated for initial moisture content 95%, and final dry seaweed 15% (wet basis). The results were depicted in Fig. 6. At lower relative humidity by air dehumidification, the equilibrium moisture in material was lower. The driving force for water evaporation became higher (see Equation 1 – 3). As consequence, the drying time can be shorter and product can be fully dried[1,11]. However, the air dehumidification effect was not significant at operational temperature upper 50°C. Based on Figure 6, the air temperature, affected drying time significantly. At higher temperature, the drying rate increased. Thus, more water can be evaporated in which shortened drying time.

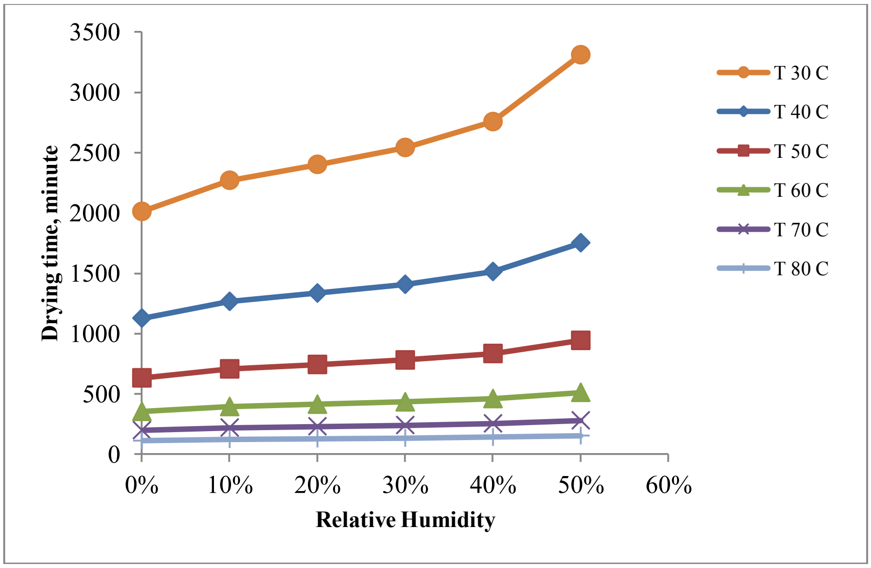

Fig. 6. Drying time on various air relative humidity (% RH) and temperature estimated by Page model at 5.0 m.s^{-1} (for 40^{o}C (T 40C), 60^{o}C (T 50C), and 70^{o}C (T 70C))

4. Conclusion

The performance of seaweed drying with and without zeolite was compared based on constant of drying rate as well as drying time. Zeolite was used to dehumidify air in which affected water removal positively. The air temperature and air velocity also influenced the water removal from seaweed. Higher air temperature and air velocity resulted faster water removal. With faster water removal, the drying time became shorter. Moreover, the air temperature 70^{o}C or below resulted reasonable seaweed quality.

The constant of drying kinetic for three type predictive models namely Newton, Page, and Henderson & Pabis have been also developed and validated. After evaluating by minimum sum of square error (SSE), the Page model was the most favorable to describe seaweed drying. This model was then used to predict drying time to dry seaweed from 95% water content up to 15% at various air temperature and relative humidity. The result showed drying time was shorter at higher temperature or low relative humidity. Higher temperature increased moisture diffusivity as well as contant of drying rate. While, low relative humidity enhanced the driving force for drying. Then, the water removal became faster in which shortened drying time.

Acknowledgement

This research was conducted in Laboratory of Process Engineering Department of Chemical Engineering Faculty of Engineering, Diponegoro University. The program was funded by Directorate of Research and Community Service, DGHE (DIKTI), Ministry of Education and Culture, Indonesia, 2014.

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