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Design of Eco-friendly Fixed Bed Dryer Based on A Combination of Solar Collector and Photovoltaic Module

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ABSTRACT

A study to develop a convective eco-friendly fixed-bed solar dryer is presented in this article. The aim of this study was to design an efficient eco-friendly fixed bed dryer using solar collector and solar photovoltaic panel with a forced convective system. The design consists of a V-corrugated solar collector, a centrifugal fan, a solar photovoltaic module (100 WP) and a drying unit in the mini-silo model with five layers. The dryer performance test was conducted in September, October, and November 2017 in Malang, East Java, Indonesia. The observation showed that the temperature of the solar collector and the first layer of the drying unit could reach 40-70°C on a sunny day and 30-50°C in cloudy/rainy conditions. The efficiency of the daily collector varied from 20% to 50%. Based on a multiple regression analysis, it showed that some variables (solar intensity, voltage of photovoltaic panel, air speed around the blower, air collector velocity, collector relative humidity, ambient temperature and relative humidity temperature) significantly influenced the collector temperature. The result of drying simulation using red pepper showed that the design has a potential to be used as an eco-friendly fixed bed convective drying. Based on the empirical model, the drying time needed to reach 12% of moisture content (wet basis), respectively, was 5-6 days for the first tray, 8-9 days for the second tray and 9-10 days for the third tray in rainy season.

INTRODUCTION

Drying activities in agricultural products have been carried out for centuries as an alternative processing for enhancing shelf life, reducing volume, minimizing microbial activities, improving flavour and increasing economic value (Prakash & Kumar 2014, Agrawal & Savriya 2016, Naderinezhad et al. 2016). In general, drying is defined as a water removal process through complex and simultaneous concepts of heat and mass transfer with a high energy demand (Sebaii & Shalaby 2012, Mujumdar 2010). It is a complicated process that requires the highest energy consumption compared to other food processing technology. A drying consumes 55% of energy in total energy needed for food preparation, while harvesting process needs 15%, cultivation consumes 10%, sowing needs 10% and transportation consumes 6% (Jerald 2013). Strumillo (2006) estimated 12% on average of energy utilized in the manufacturing process is consumed by industrial drying.

Rural farmers in Indonesia usually use direct sunlight in open areas to dry agricultural products. This method is slow, labour-intensive, time-consuming and requires a large open space. It also depends to a large extent on the availability of sunlight (Bennamoun & Belhamri 2003, Fudholi et al. 2014, Aghbashlo et al. 2015). This process produces low quality and quantity of dry products due to contamination by dust and dirt. The products also have a high risk of spoiling due to rain, wind, and moisture imbalance, so they cannot meet the international standard quality demand (Mustayen et al. 2014). The total amount of dry products can also be reduced during the drying process due to the attack possibility by birds, rodents, and insects (Prakash & Kumar 2013). Choucia et al. (2014) said that the main problem in an open air-sun drying method is the limitation in the control of some factors that influence the drying process.

Therefore, research was carried out to innovate and optimize the use of solar energy to solve problems in the

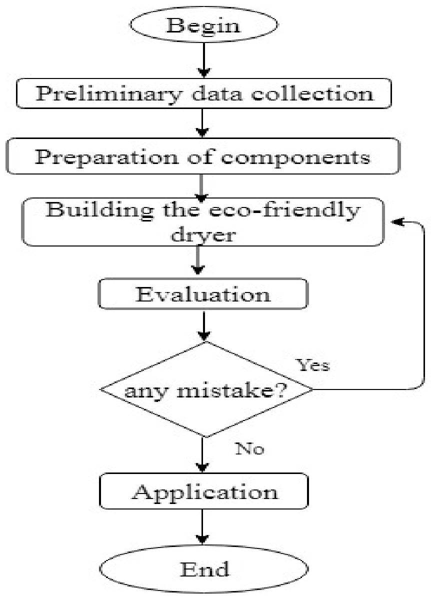


Fig. 1: Flow diagram of the dryer design process.

natural solar drying method (Mustayen et al. 2014). A properly designed solar dryer can reduce the disadvantage of sun drying and improve the quality of drying products (Hossain & Bala 2005). Kaewkiew et al. (2012) made an observation about drying models in the greenhouse for the drying of red peppers on a large scale (with room dimensions of $8 \times 20 \times 3.5$ m^3). It used 9 volt DC fans that operated with electrical energy derived from a photovoltaic module. This method resulted in a significant reduction in drying time as compared to drying under the sun. The colour of the red peppers was also better than the natural samples dried in the sun. The design disseminated to the small-scale agriculture drying industries in Thailand.

Some researchers worked with photovoltaic solar technology dryers. They proposed ideas to drive the fan in the forced convection drying system. The model will allow a convective dryer to be used in remote areas that have no connection to the electricity grid. The result showed that greenhouse drying under forced convection using photovoltaics were more suitable for crops with high moisture content (e.g. vegetables and fruits) and greenhouse drying under natural convection was better for crops with low moisture content (Prakash & Kumar 2014, Hossain & Bala 2005, Banout et al. 2011, Bala 2005, Chen et al. 2010). Chouicha et al. (2013) using a hybrid photovoltaic and solar thermal dryer to support a better drying system. The electrical energy generated from the photovoltaic modules used to turn on the heaters when the solar intensity decreases.

Due to our knowledge, the design of a fixed bed dryer model for horticultural products with a forced convective system that uses a solar collector and a photovoltaic panel to produce good quality dry products with an efficient drying time is not popular yet. Aghbashlo et al. (2015) stated that a deep/fixed bed drying technology is one of the most used for the drying of the heterogeneous biological material. This technique places the materials in a fixed bed of more than 20 cm thick.

A research development based on a combination of solar and photovoltaic collectors on agricultural products is important to do, to support solar energy development in Indonesia mainly to solve the high damage of horticultural products problem and the difficulty of electricity and fuel access in some remote areas of Indonesia. As a tropical country, Indonesia receives abundant solar radiation (16 MJ/day) (Batubara et al. 2017). Handayani & Ariyanti (2012) said that the average daily radiation in most areas in Indonesia is about 4 KWH/m^2. Optimizing the use of solar energy is a good option to solve post-harvest problems, mainly for perishable crops.

Small farmers need adequate information on the use of solar energy such as heat and energy resources to get high quality dry agricultural products. The aim of this study was to design an efficient and eco-friendly fixed bed dryer using solar collector and solar photovoltaic panel with a forced convective system. This work will support the development and strengthen the use of solar energy as an environmentally friendly resource of renewable energy for farmers in rural areas.

MATERIALS AND METHODS

Design consideration: The design concept developed in this study is based on an eco-friendly fixed bed dryer on a combination of solar collectors and photovoltaic solar panels. The dryer is expected to produce high quality dry agricultural products. The developed technology is a forced convective fixed bed dryer which uses solar collectors and

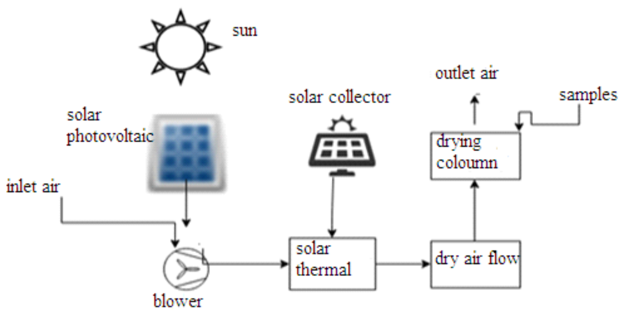


Fig. 2: Concept and principle of operation of the fixed bed respectful with the environment through solar collector solar photovoltaic (adopted and modified by Akpinar & Bicer 2008).

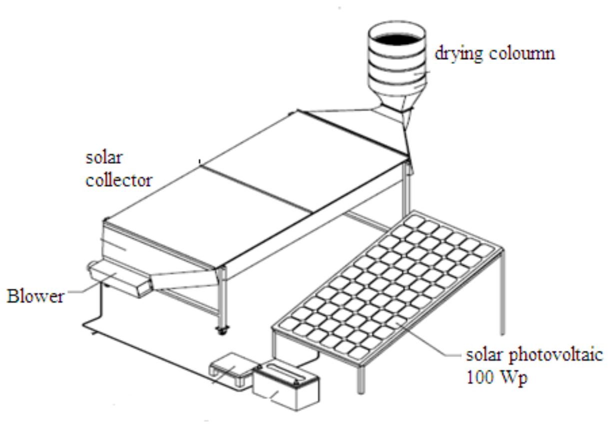
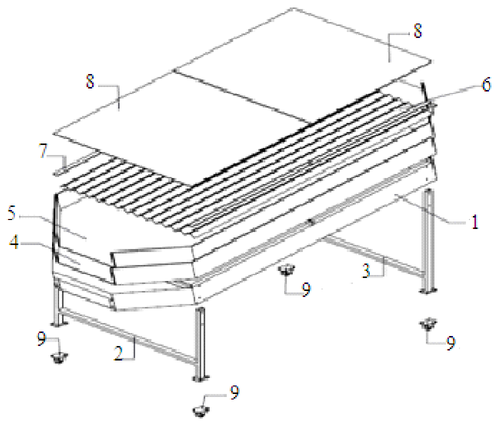


Fig. 3: Schematic view of eco-friendly forced convective fixed bed dryer using solar collector and solar photovoltaic.



Part No.	Part Name	QTY	Material
1	Chamber	1	Stainless steel
2	Feet A	1	Steel
3	Feet B	1	Steel
4	Glasswool isolato	1	Glasswool
5	Sheet Isolator	1	Alumunium Sheet
6	Heat Absorber	1	Iron Sheet
7	Rubber protector	4	Rubber
8	Glass panel	2	Glass
9	Polley Trolley	4	

Fig. 4: Schematic view of solar collector.

photovoltaic modules. The design process was carried out through some steps, as shown in Fig. 1.

The variables measured to figure the dryer function are ambient temperature, relative humidity of the environment, collector temperature, relative humidity of the collector, inlet temperature of drying, relative humidity of the drying inlet, solar intensity, electrical energy generated by the photovoltaic and air drying speed. Fig. 2 shows the concept and operating principle of the dryer designed in this study.

Fig. 2 shows that the basic principle of the dryer is a process of heating the air in the collector, moved by a blower supported by the electricity resulted from the photovoltaic panel. The heated air with a certain speed will pass the layers of the product in the drying column with a fixed bed concept.

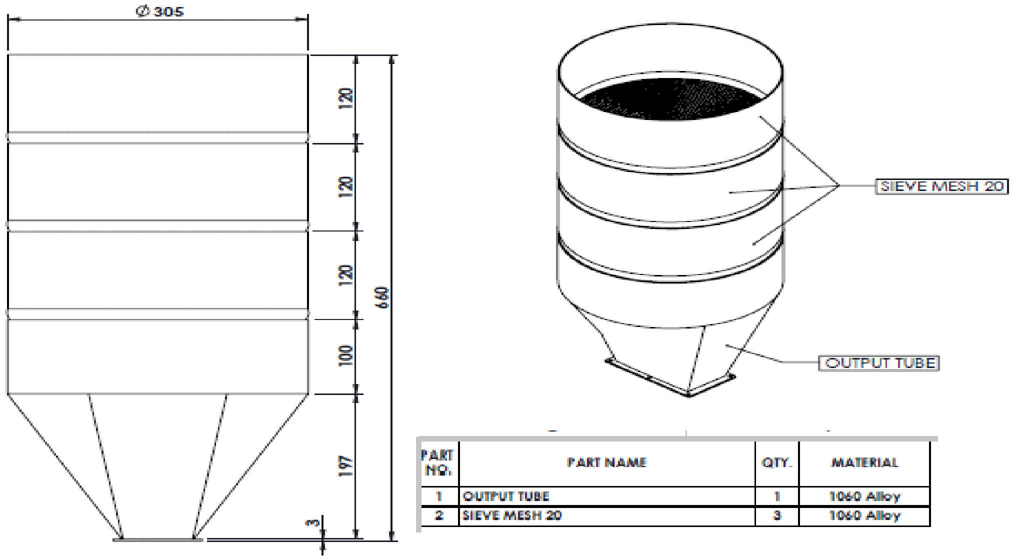
Instrumentation: The dryer consists of four parts: a collector, a solar photovoltaic panel, a drying unit in a silo model and a blower. The measuring tools used in this study were a thermometer, hygrometer, lux meter, wind meter, and digital balance.

Solar collector: A solar collector is the most important part of an active solar drying system (Fig. 4). The solar collector will gather solar energy, transform its radiation into heat and transfer heat through the fluid inside the collector (Hematian et al. 2012). In this investigation, the solar absorber collector was a V-groove iron plate (0.55 mm thick), painted in black and mounted in a box made in the same area. The lower part of the absorber was insulated with 19 mm thick glass wool. To create a greenhouse effect, a transparent glass sheet of a 4 mm thick layer was placed on the absorber. The total length, width, and height of the solar collector are 1500, 800 and 200 mm, respectively. According to Sebaii & Shalaby (2012), the V-groove collector had an efficiency of 7-12% higher than a flat plate collector.

Solar photovoltaic module: The photovoltaic solar module used in this study was polycrystalline with 72 cells equal to 100 WP. It converts solar energy into electricity to support the centrifugal fan. The dimension of the photovoltaic panel is 1020 mm × 670 mm × 30 mm. The photovoltaic panel produces 16-18 volts, respectively, according to the solar intensity. The photovoltaic module has been certified by the Agency for the Evaluation and Application of Technology, Republic of Indonesia (certificate number: 2016079).

Blower: The centrifugal blower (ORIX-FO107) used in this study has the following specification: motor diameter: 7.7 cm, length: 30.5, blower diameter: 7.3 cm, total fan wings: 26, maximum voltage: 24 volts and maximum speed: 5 m/s.

The drying unit: The drying unit adopted a silo model, with 30 cm in diameter and 7 cm in height for each layer/ tray (Fig. 5). It consists of 5 trays. The total volume of each tray is 537.075 cm^3, it is equal to 1-1.5 kg of red pepper. The drying trays were constructed with fine mesh for the drying air that passes through the elements of the material. Hot air



PART NO.	PART NAME	QTY.	MATERIAL
1	OUTPUT TUBE	1	1060 Alloy
2	SIEVE MESH 20	3	1060 Alloy

Fig. 5: Schematic view of drying coloumn.

passes through the trays directly from the solar collector.

Performance evaluation of the solar dryer: The principle that governs the transfer of heat within a solar collector is the greenhouse effect. It occurred when solar radiation passes the transparent cover of the collector and is absorbed by the V-shaped plate inside. The plate will return the radiation to the inner side of the cover, where it will return to the plate. During this process, the fluid between the plate and the cover will absorb the energy. Almiron & Lara (2016) said that the thermal efficiency of the solar collector is affected by solar intensity, fluid density, heat capacity and fluid velocity. In order to determine the performance of the dryer, including the thermal efficiency of the collector, an experimental study was conducted in September, October and November 2017.

During the performance test process, the temperature and relative humidity of the environment, internal collector and air inlet to the drying unit were measured with a standard digital thermometer and hygrometer. The device was calibrated using a wet mercury bulb laboratory thermometer. The solar intensity was measured with a lux meter, with a one-hour interval between 07:00 a.m. and 16. 00 p.m. at the local time. The airspeed around the blower and the outlet collector area/inlet drying unit were measured by a wind meter. The data were collected in September, October and November 2017. It was the beginning of the rainy season in September and peak season in November.

The efficiency of the solar collector is the ratio of useful energy in the solar collector to the solar energy arrived on the surface of the solar collector (Hematian et al. 2012). Referred from Bennamoun (2012), collector efficiency in this convective solar drying system supported by solar thermal collector and solar photovoltaic panel was determined by the following equation:

$$\eta = \frac{Q_{useful}}{Qsc + Qpv} x\ 100 \qquad ...(1)$$

Where, *Qsc* is the energy gained by solar collector and *Qpv* is the energy gained by solar photovoltaic panel. The useful energy is determined by the following equation:

$$Q_{useful} = m.C_p.(T_c - T_a) \quad \text{(Watt)} \qquad ...(2)$$

Where, Cp is the specific heat capacity of the air at constant pressure (J/kg/°C) and (*Tc*-*Ta*) is the temperature difference of ambient and solar collector output. *m* is the mass of the air flow, and is determined by the following equation:

$$m = \rho.A.V \quad \text{(kg/s)} \qquad ...(3)$$

Where, ρ is the fluid density/moist air density, *A* is the collector absorber surface and *V* is the air velocity.

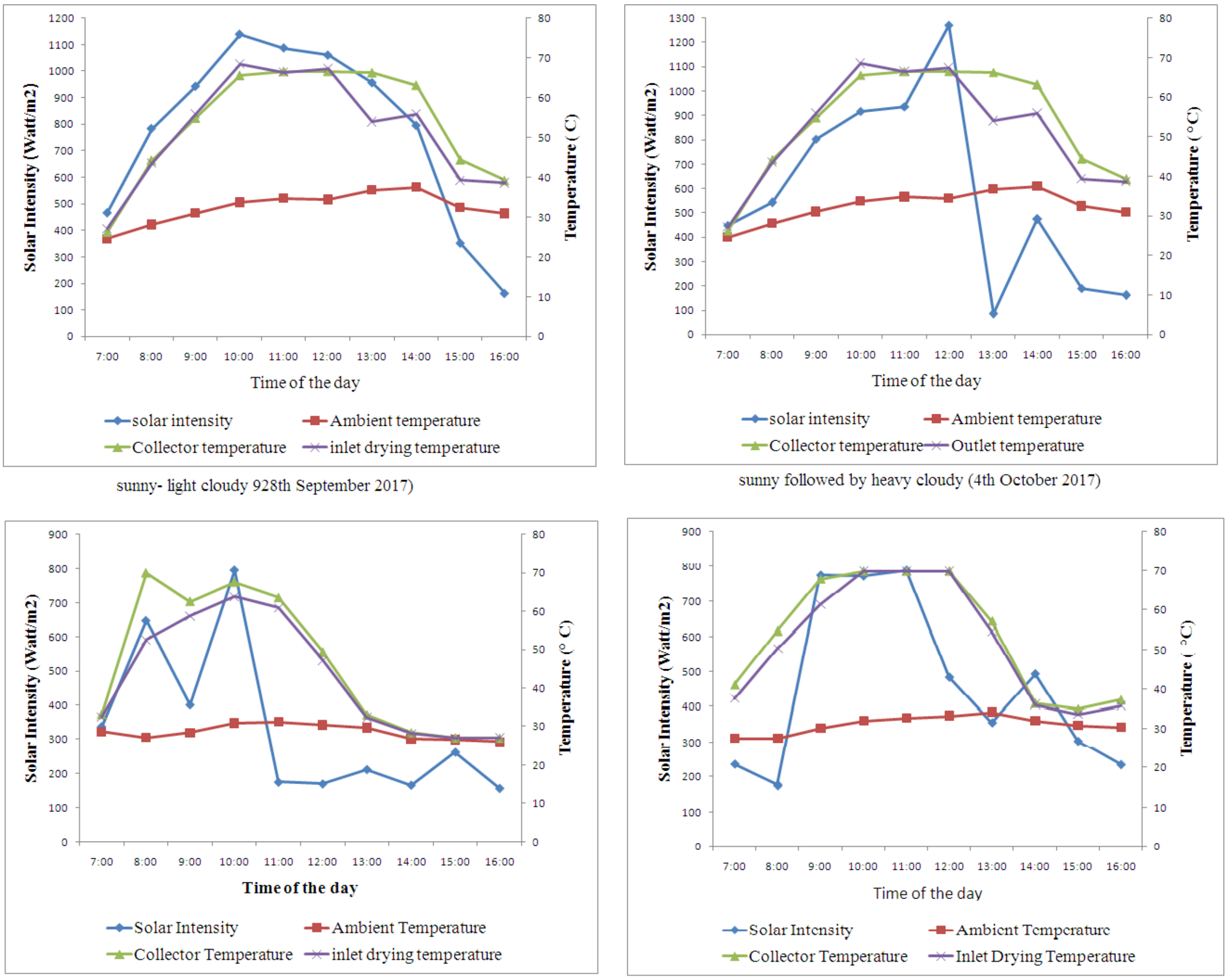
Qsc is determined by the following equation :

$$Qsc = I.Ac \quad \text{(Watt)} \qquad ...(4)$$

Where, *I* is the global solar intensity (W/m^2) and *Ac* is solar collector width, *Q pv* is determined by:

$$Qpv = Vpv * icurrent \quad \text{(Watt)} \qquad ...(5)$$

According to the photovoltaic guidance information the rates of I current is 5.69 Ampere. The lost energy in the collector and photovoltaic panel was ignored.



sunny- light cloudy 928th September 2017)

sunny followed by heavy cloudy (4th October 2017)

light sunny-mid cloudy-rain (8th October 2017)

sunny-heavy cloudy-light rain (10th October 2017)

Fig. 6: Drier temperature performance rates in various weather condition.

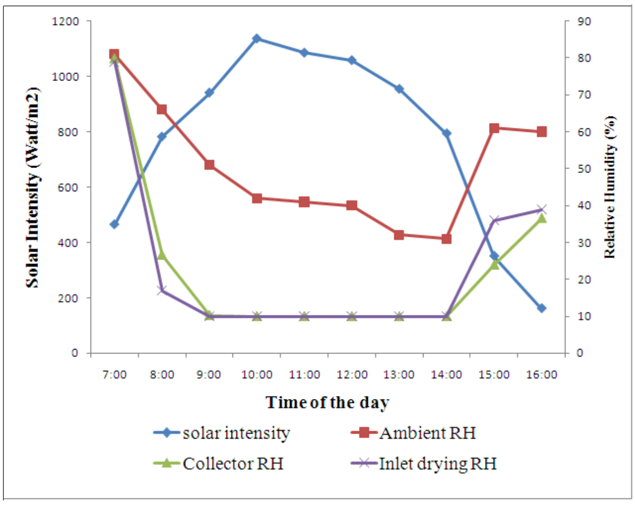
To predict the fitted model and the most influential factor of the dryer performance, a multiple regression analysis was done. The solar collector temperature was the dependent variable and solar intensity, voltage photovoltaic, air-speed around the blower, air collector velocity, collector relative humidity, ambient temperature and relative humidity temperature were independent variables. Zhu & Chen (2013) reported the using of regression analysis based on experimental data as a simplified method for thermal responsive performance of passive solar house in China. Kicsiny (2014) proposed a multiple linear regression based model for solar collectors. The result of the study showed that MLR based model has a good precision and can be easily applied to many collectors in practice.

The data in this study were tested by collinearity, heteroscedasticity, autocorrelation, and residual normality test to make sure that they fit to be analysed by multiple regressions.

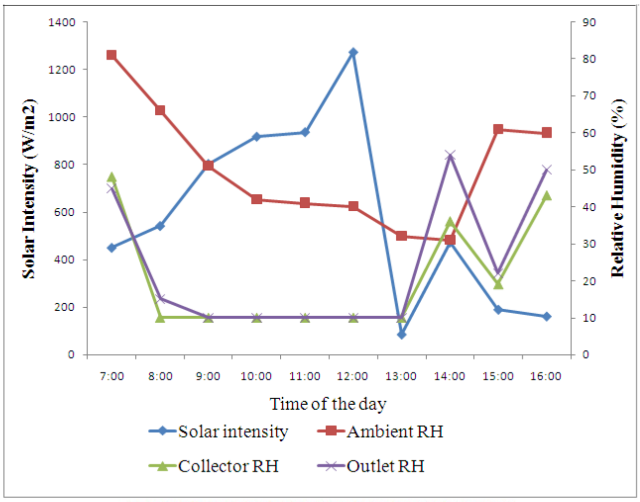
Drying implementation: Drying implementation was done on red pepper on 8-10 October 2017. The drying time was 6 hours/day (between 7.00-14.00), two hours shorter than the targeted time due to the inappropriate weather in the afternoon. Fresh red peppers from the local market were used as the simulation drying product. The main parameter observed was the decrease of moisture content.

RESULTS AND DISCUSSION

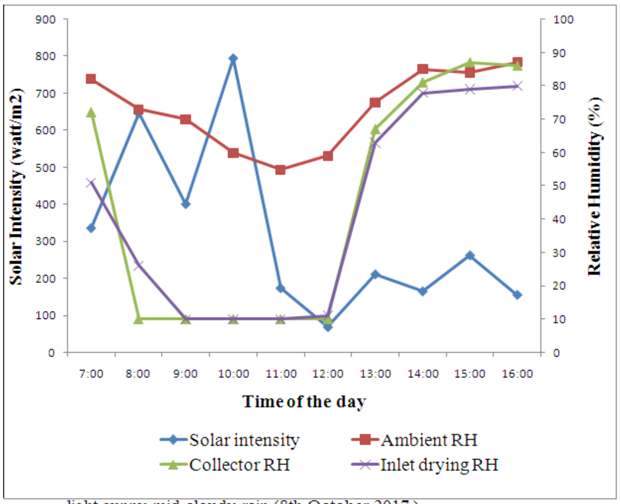
The schematic view: The schematic view of the dryer can be seen in Fig. 3. It shows that the dryer has some important parts : solar collector, solar photovoltaic panel, blower and drying column. The solar dryer was designed and produced



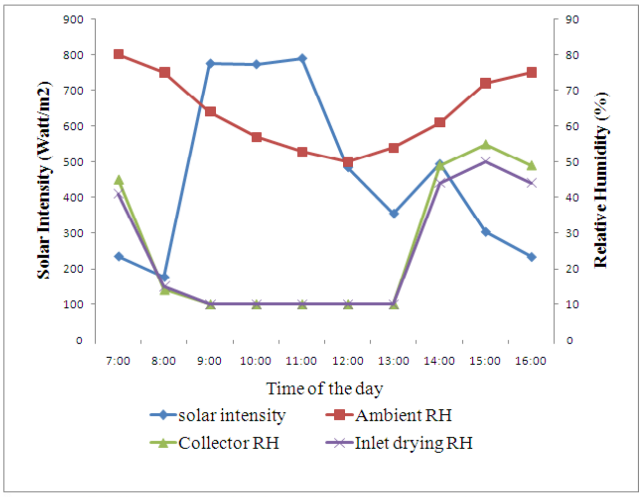
sunny- light cloudy (28th September 2017)



sunny followed by heavy cloudy (4th October 2017)



light sunny-mid cloudy-rain (8th October 2017)



sunny-heavy cloudy-light rain (10th October 2017)

Fig. 7: Relative humidity of solar dryers in various weather condition.

in the Agricultural Engineering Laboratory of Brawijaya Malang, Indonesia. It is an ecological solar dryer that converts solar energy into thermal energy through a solar collector and electricity through a polycrystalline photovoltaic module to support the blower. The designing and building process was taken 4 months from May to August 2017. The air was moved by a centrifugal fan (DC 24 V) and air passed the surface of the solar collector to the drying column. The air was forced to move using the fan powered by photovoltaic electricity, to accelerate the drying process.

Solar Dryer Performance

***Temperature*:** The outlet air temperature of the collector and the inlet air temperature of the drying unit were relatively higher than the ambient temperature. On sunny days, the temperature of the first tray can reach 70°C. It happened at 10.00-12.00 when the solar intensity was > 1000 W/m^2. The solar intensity gradually increased from 465.6 W/m^2 in the morning to 1131 W/m^2 at 10.00-12.00. It gradually decreased to 161. 99 W/m^2 at 16.00 p.m.

The performance test of the solar dryer was also conducted in rainy/cloudy circumstances, occurred in the afternoon. The temperature of the solar collector and the inlet air temperature to drying unit decreased along with the decrease of solar intensity due to the cloud and the rain condition. Fig 6 shows that, in general, temperature of the solar collector and inlet drying area was relatively higher than environmental temperature both in sunny day or hostile condition. According to Sharma et al. (1993) and Mustayen et al. (2014), an indirect-type solar dryer using

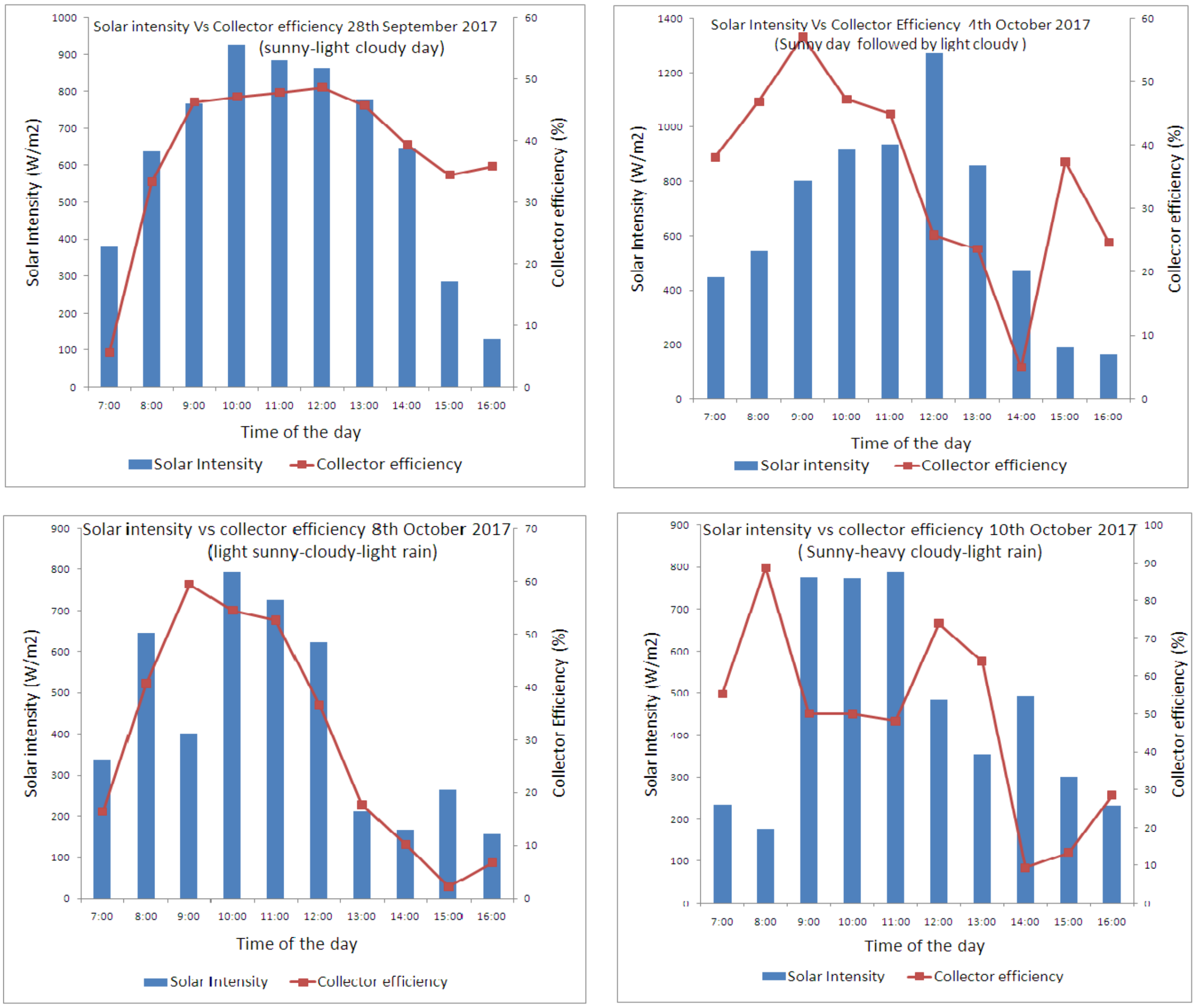


Fig. 8: Daily solar radiation and solar collector efficiency in various weather conditions.

active solar collector is still capable of giving good output under bad weather condition. Wulandani and Oscar (2009) justified that the drying of the solar-powered greenhouse with forced convection system has a more stable temperature performance than the greenhouse drying system with natural convection.

***Relative humidity*:** Fig. 7 showed that relative humidity of the solar collector and air inlet in clear sky day was stable at 10%, after one-hour drying in sunny days condition. It remained stable for 5.5 hours forward. The relative humidity began to increase in the afternoon (after 15.00 pm). Low relative humidity (10%) is the best condition in a drying process. It can be said that this dryer had sufficient relative humidity to support a drying process. In cloudy/rainy condition, relative humidity in inlet drying seemed unstable. It seemed that, although it is possible to carry out a drying process on cloudy days according to the inlet drying temperature, which was higher than ambient temperature, it was not supported by the relative humidity of the collector and the drying unit.

***Solar collector efficiency*:** Thermal collector efficiency depends on the type of collector absorber, covered material, air velocity and collector width (Hematian et al. 2012). Based on the data which were taken on 28 September, 4 October, 8-12 October 2017 and equations 1-6, solar collector efficiency is shown in Fig. 8. The efficiency in cloudy/rainy days was higher than the efficiency in the sunny days. It can happen because the collector has a good function as an energy saving, so while the solar intensity decreases, it still keeps the energy gained before the cloudy/

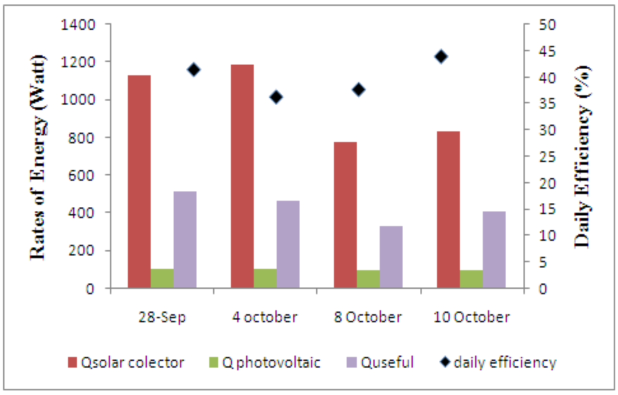


Fig. 9: Daily rates of energy gained by solar collector and solar photovoltaic, useful energy and collector efficiency.

rainy conditions. Hermatian et al. (2012) in his study showed that the efficiency of convective solar collector has ascending tendency until the evening (the research was done from 09.00-20.00). It is similar with the result of this study, where the ascending tendency happened in 28th September 2017 when the weather is in a good condition (clear sky with a light cloudy). Hii & Law (2012) and Batubara et al. (2017) stated that the higher the intensity of solar energy received in the solar collector, the solar collector efficiency also will be higher in a normal weather condition. In the days of unstable weather (4th October, 8th October and 10th October 2017), the trend of efficiency cannot be predicted properly.

Rates of daily energy collected from the solar collector and solar photovoltaic panel compared with useful energy are shown in Fig. 9. Rates of daily efficiency of the collector varied from 36-44%, depending on solar intensity rates and the weather. Total energy gained in clear sky days is higher than that in unstable weather days.

Regression and correlation of solar intensity, photovoltaic voltage, air flow, temperature and relative humidity: Based on the data taken on 12-15 November 2017 a multivariate regression analysis was done. It aimed to find the most influenced variables for collector performance. The residual normality test that was done using Anderson-Darling Statistic Test (Razali & Wah 2011) showed a normal result. The weather on the observation days was mid cloudy before noon, and heavy cloudy followed by rain after midnoon. Solar intensity observed was 75-790 W/m^2, ambient humidity was 44%-77%, the ambient temperature was 27.1-34.10, collector humidity variation was 11-54% and collector temperature variation was 31-57°C. Dependent variable determined in the analysis was the collector temperature. The independent variables were solar intensity, voltage photovoltaic panel, airspeed around the blower, air collector velocity, collector relative humidity, ambient temperature and relative humidity.

The heteroscedasticity test showed an appropriate result for the data of variables to be analysed by multivariate regression. The data were also non-multicollinear and non-autocorrelation. The regression statistic result is given in Table 1.

Based on the information from Table 1, the linear model to simplify the relationship of a dependent variable (collector temperature) and independent variables is described in the following equation :

$$Y = 138.54 + 0.011x_1 - 1.81x_2 - 2.273x_3 + 7.45x_4 - 0.44x_5 - 1.13x_6 - 0.34x_7$$

Where, Y: collector temperature, x1: solar intensity, x2: voltage photovoltaic, x3: velocity around the blower, x4: collector velocity, x5: collector relative humidity, x6: ambient temperature, and x7 is ambient relative humidity. The model is fitted with the data, shown by the value of adjusted R^2 (0,93). This value means that 93% of the variations in the collector temperature changes can be explained by dependent variables in this investigation (x_1-x_7) and the other 7% depends on the other variables excluded in this investigation.

The probability value showed that solar intensity, voltage photovoltaic panel, air collector velocity, collector

Table 1: Regression statistical result.

Regression statistic			Coefficient	P-value
Multiple R	0,9764	Intercept	138.54	0,0164
R Square	0,953357	Solar Intensity (watt/cm2	0.011	0,005911*
Adjusted R Square	0,930036	Voltage Photovoltaic	-1.81	0,028666*
Standard Error	1,969358	Velocity around the blower	-2.27	0,808388
Observations	22	Air collector velocity	7.45	0,033206*
Significance F model	2,92815E-08	collector humidity	-0.44	9,92E-05*
Significance F heteroscesdasticity	2,62E-16	Ambient Temperature	-1.12	0,172443
		Ambient Humidity	-0.34	0,002383*

*significant (p<0.05)

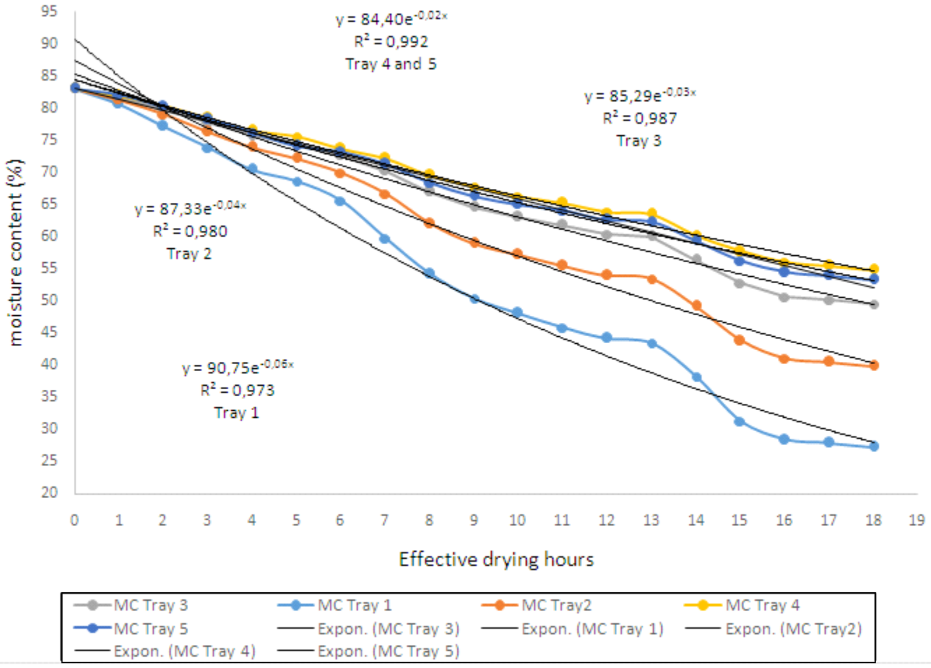


Fig. 10: Drying rates of red pepper using eco-friendly fixed bed dryer based on a combination of solar collector and solar photovoltaic panel (8-10 October 2017).

humidity and ambient humidity gave a significant influence to the solar collector temperature (p<0,05). In rainy condition, it seems that ambient temperature did not give a significant influence on the rates of collector temperature. Afriyie et al. (2013) reported that the relative humidity of the environment greatly affects the drying process with solar energy. Batubara et al. (2017) said that the inside collector temperature is strongly influenced by solar intensity.

Drying implementation: In a fixed bed drying process, the product is filled in thick layers so that the drying column can be supposed as porous media (Bennamoun 2012). Fig. 10 showed that drying rates of the red pepper in the first trays were the fastest, and the drying rates of the fourth and fifth trays were the lowest.

Statistically, there is no significant difference on drying rates based on ANOVA test (p<0,05). The drying rates were varied between 2.96 % moisture content/hour and 1.51 % moisture content/hour. Although the final moisture content of the pepper was not adequate yet, the model can be used to predict the time needed to dry hot pepper in a rainy season using the eco-friendly fixed bed dryer based on a combination of solar collector and solar photovoltaic panel.

Based on the exponential empirical model, the drying time needed to reach 12% of moisture content (wet basis), respectively, was 33,72 hours (5-6 days) for the first tray (0-7 cm thick), 49.61 (6-7 days) hours for the second tray (7-14 cm thick) and 65.37 hours for the third tray. It seems that in the rainy seasons, the drying is only possible to do in the first and second tray. It is not suggested using the higher trays due to the longer drying time.

CONCLUSIONS

This research developed a design of an eco-friendly convective fixed bed dryer with a combination of solar collector and solar photovoltaic panel. Collector efficiency was measured as a representative of the dryer performance. A multiple regression analysis was done to decide the most important variables influencing the performance. The result showed that the collector temperature can reach 70°C in sunny days and 50°C in cloudy/rainy conditions, the efficiency of solar collector varied from 30-50%, and the collector has a relatively stable performance in cloudy/rainy conditions. The multiple regression analysis showed that solar intensity, voltage of photovoltaic panel, air collector velocity, collector humidity and ambient humidity significantly influence the solar collector temperature in the drying system. The result of drying implementation using red pepper as the drying product showed that the drying time needed to reach 12% of moisture content (wet basis), respectively, was 5-6 days for the first tray (0-7 cm thick), 8-9 days for the second trays (7-14 cm thick) and 9-10 days for the third tray in rainy season.

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