

Study on Solar Dryer with Rotating Rack for Cocoa Beans

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ABSTRACT

This study discusses the engineering aspect of solar-assisted drying for cocoa beans using GHE type dryer with rotating rack. This dryer has a capacity of 60.5 kg/m^3 . Solar irradiation and charcoal combustion were used as the thermal energy sources. Thin layer drying was performed in order to obtain drying kinetics, thermophysical properties related to drying process as well as the benchmark for field experiment. The air temperature influenced drying rate in all periods, while air velocity as well as absolute humidity did mainly just in the beginning period. The equations of the thermophysical properties related to air conditions have multiple polynomial. Individually, the validation of the properties, which were substituted to the moisture content – time equation showed a good correlation, in which all of the CODs were above 99%. Performance test of the solar dryer was carried out under the weather condition of Bogor, in order to obtain the parameters, which involved the changes of temperature, humidity and moisture content during drying. In addition, measurement of the torque and power requirements to rotate the rack as well as quality evaluation of the dried product were also conducted. The result showed that the average drying air temperatures of the solar dryer were $39.5^\circ\text{C} - 40.5^\circ\text{C}$, while the drying time ranged from 34.7 to 46.6 hours. During the tempering period, desorption process occurred. In the final stage of test II, however, moisture re-adsorption occurred in the tempering period due to the quite low moisture content of the beans. The torque requirement was relatively small, i.e., $6.4 - 10.2 \text{ Nm}$ with equivalent power of $18.6 - 29.9 \text{ W}$. The quality parameters of dried beans of the experiment were in the required general conditions for trading purposes. Measurement of solar irradiation, fuel consumption and electrical power were intended to calculate energy efficiency. The specific energy consumptions were $7.63 - 9.68 \text{ kJ/kg}$ of water evaporated. These values were much lower than those resulted from the previous study on tray drying for cocoa beans (Nelwan, 1997) and were approximately equal to the result of Manalu (1999) using bed dryer. Excluding solar energy, the thermal efficiency was between $30.6 - 44.7\%$. Development of mathematical modeling was based on both spatial and lump approaches. The first used finite volume method for three-dimensional distribution, while the second employed finite difference of Adams Moulton method. The solutions were arranged in Visual Basic 6.0 codes. Using this approach, change of temperature, RH and moisture content during the drying process were successfully predicted. The CODs between measured and calculated temperature, RH and moisture content were 0.91, 0.75 and 0.99, respectively. Simulation was performed by using lump approach. Fuzzy logic controlling was applied to obtain the effective change of the combustion rate and airflow rate. By using the logic controlling, the drying time can be shortened with considerable low energy consumption. In addition, this method could provide low drying cost, i.e., Rp. 297 per kg wet beans.

Keywords: solar-assisted drying, rotating rack, cocoa beans, drying kinetics, mathematical modeling

1. INTRODUCTION

1.1 Background

The rapid depletion of our oil reserve, with R/P (Reserve/Production) of 18 years will force Indonesia to find alternative energy supply to sustain economic development. The Kyoto Protocol requires that in order to maintain sustainable development, countries should reduce their GHG emissions about 5% below the 1990 level. In order to achieve this commitment these countries will rely on the increasing use of renewable energy, improve energy efficiency and other means for GHG abatement. Recently, there is an increasing trend that the countries are seeking cooperation with Indonesia by introducing CDM mechanism, which can help to acquire CER at much lower cost.

In the recent Prep Com. IV of the World Summit of Sustainable Development Conducted in Bali last year, there was a strong indication that all governments are urged to set a certain target of renewable energy share against the national primary use by the year 2010, in order to increase the accessibility of energy services to the poor in line with the Agenda 21, Millennium Declaration and the WSSD action program for poverty eradication. Following the result of the Prep Com IV of the WSSD, the Indonesian government had issued a draft policy called, "the green energy insight" showing an increasing commitment toward renewable energy development and adoption in the country, and consequently it is expected that the share of renewable energy development and adoption in the country, and consequently it is expected that the share of renewable energy in the national energy mix will significantly increase in the near future. One of the immediate applications of renewable energy for poverty alleviation is by directing its use in increasing the quality of agricultural products, which will lead to the increasing income and job opportunity of the farmer and the rural people.

Drying is one of popular method of post harvest handling of agricultural products in order to maintain its quality during long period of storage. Without drying, the freshly harvested agricultural products, such as cocoa beans, will gradually deteriorated and decomposed due to enzymatic reactions and infestation by moss and bacteria. Cocoa beans are dried after being fermented to produce good quality product. After fermentation, the beans outer layer is usually become sticky and forming conglomerations of cocoa beans. In practice, mechanical stirrer is usually employed to break the conglomerations, to improve the drying process.

Direct utilization of solar energy (i.e. sun drying) for cocoa beans drying is a common practice even in large plantation, since it is easy and low-cost. Some disadvantages such as necessity to have wide area of drying floor and since its spread in an open space the beans are easily mixed with pebble, litters and other foreign materials and acceptable to microorganism's contamination and pest's attack.

Solar drying can be designed in such a way to reduce the disadvantages as mentioned above. Basically, there are two types of solar drying which can serve the purpose. One is using solar heat collector, which also functions as roof of a drying station and another is using the principle of a greenhouse where solar energy is trapped within a transparent structure, which in turn is used to produce the drying air. One of the merit of the latter system is that the suns rays is also utilized to heat the products directly and the cost of construction can be reduced significantly since the transparent structure where drying racks or bin located is also functions simultaneously as a heat collector. Kamaruddin, et al, 1993 had studied the application of the latter system which called greenhouse effect (GHE) solar dryer for drying of several agricultural

products in Indonesia. One series of research of cocoa and coffee beans drying using greenhouse effect solar dryer has been conducted (Kamaruddin et al. 1998). In this research, various mixing method, energy requirement analysis and simulation based on heat and mass transfer have been performed.

Test results of the above GHE solar dryer showed that using this system with an initial loading of 228 kg (60.4% m.c., w.b.) of wet cocoa beans could be dried to a final moisture content of 6.7 % w.b. within 40 hrs. Under this condition the average temperature and RH were 45.2°C and 35% respectively. Drying efficiency of the system was 18.4%.

The total specific energy for drying, using the first generation GHE solar dryer was 12.9 MJ/kg. Further study in developing new design using a drying bin equipped with mechanical stirrer and bigger loading capacity of 400 kg had improved the specific total energy for drying to 6.2 MJ/kg water evaporated (Manalu, 1999). For comparison, a commercial grain dryer using only commercial energy input, for example, the value of specific energy for drying lies in the range of 3 – 10 MJ/kg water evaporated (Bakker-Arkema and Saleh, 1985). The drying time of the latter GHE solar dryer design between 32 to 33 hours.

Due to increasing price of fuel and electricity, a new concept of GHE solar drying system, by making use the most of natural energy such as biomass and wind is now under consideration. This study is attempted to explore this possibility.

1.2 Objectives

The objectives in this research are:

1. To design and construct a rotating rack in GHE solar dryer and to obtain the general performance of the dryer system.
2. To study behaviors of relative velocity of air to beans due to the rotation of rack.
3. To develop mathematical models for air movement, heat and vapor balance and then validate the developed models with the experiment result.
4. Economic feasibility of the new system

2. METHODOLOGY

2.1. Design of the dryer system

2.1.1. Design consideration

- Greenhouse type of solar dryer is desired since it is relatively simple and cheap in construction. In addition, the dryer is adequately efficient in drying area utilization due to integration of the drying chamber and the collector.
- Tray drying is commonly performed in order to create a proper condition of air-beans contact in which the bed dryer method reaches difficultly as well as to eliminate the required power for mixing and hence the physical damage due to the mixing can be reduced. However, it is adequately complicated to generate a uniform air velocity circumstance in each tray.

- Air velocity is a significant parameter influencing drying rate, particularly in higher moisture content. A complicated arrangement has to be performed to generate a high air velocity along with keeping a certain quantity of air-mass flow rate. To overcome this limitation, it might be better to move the tray relative to the drying air, so that the necessary air velocity enclosed to the beans will be reached. Rotating movement of the tray is considered to be a technique that is sufficiently simple to obtain such a condition. A low rotating movement may provide such the air relative-velocity.
- In order to obtain an effective system, the rotating movement is employed as the air driver. To facilitate this, the tray is necessary to be curved such as the fan blade shape, so that the rotating movement of tray will deflect the air. The dryer wall is required to be fitted like axial blower housing to keep the airflow run properly. Hence, the air flows continuously to carry heat and moisture without a fan. Since the tray is not a good propeller and its rotating velocity is relatively low, the drying-air mass flow rate can be kept at a sufficient charge.
- While the static tray need a certain space (slit) to allow the airflow, the air relative-velocity to the beans make the dryer can be designed with a more narrow slit. Therefore, a more number of trays can be located in the same space volume, which means the beans capacity is increased.

2.1.2. Drying process

- The transparent wall transmits solar irradiation and this passing-through-irradiation will be absorbed by the blackened plate. Temperature of the plate will rise so that a temperature difference between drying air and the plate exists. Due to the difference, heat exchange between the both of components.
- The air movement due to tray motion will affect the air layer adjacent to the plate, hence airflow between tray and plate will be performed. When the heated air blow the beans, temperature of the beans begin to rise and drying process exists. Subsequently, moisture from the beans will enter to the airflow stream.

2.2. Mathematical Modeling

The main objective of development of mathematical models to this system is to predict change of temperature and humidity of both beans and drying air during the process. The first stage in the modeling is to separate the drying system into their components (subsystems) on which the change of parameters will be investigated. The next stage, based on the heat balance for each component and moisture balance for air and beans, mathematical model might be expressed in the subsystems.

2.2.1. Air in drying room

In the drying room, surface heat transfers include those that transfer to or from the absorber plate, flat floor and the wall. In addition, there is also heat transfer due to the fluid flow. This fluid flow (i.e. air flow) is necessary in order to maintain the air humidity inside the room. This action, however, results loss of heat, where the higher temperature of drying air replaced by the lower temperature of surrounding air.

The heat balance of air in drying room is expressed as follow:

$$\frac{dq_r}{d\theta} = \dot{m}_u C_{p_r} (t_{amb} - t_r) - U_d A_d (t_r - t_{amb}) - h_{abs} A_{abs} (t_{rmb} - t_{abs}) - h_p A_p (t_r - t_p) - h_{p,up} A_{p,up} (t_r - t_{p,up}) - U_f A_f (t_r - t_{sto}) \quad (1)$$

After some rearrangements the equation will be:

$$m_a (C_{p_a} + C_{p_s} H_r) \frac{d(t_a)}{d\theta} = -m_a H_r (C_{p_w} - a2 - C_{p_s}) \frac{dt_{dp}}{d\theta} - m_a (a1 + tdp (C_{p_w} - a2 - C_{p_s}) + C_{p_s} t_a) \frac{dH_r}{d\theta} + hA(t_p - t_a) + hA(t_{p,up} - t_a) + hA(t_{abs} - t_a) + UA(t_{sto} - t_a) + \dot{m}_v h_{fg} + \dot{m}_a (C_{p_a} + C_{p_s} H_{amb}) \dot{t}_{amb} + \dot{m}_a (C_{p_a} + C_{p_s} H_r) \dot{t}_a \quad (2)$$

In the calculation, all the specific heats except for liquid water, are the function of air temperature. Dry air temperature, is equivalent to the moist air (i.e. in this case: drying air) temperature, since they are in equilibrium condition.

2.2.2. Absorber plate

The blackened plate is utilized to absorb solar irradiation and hence the temperature of the plate increases. When solar irradiation passes through a transparent material, a part of the irradiation is reflected and the rest is transmitted into the inner side. After through the drying wall, solar irradiation strikes the absorber plate and greatest part of it will be absorbed proportional to the plate absorptivity. Then, heat transfer due to the surface convection occurs, where generally the heat leaves the plate since the temperature difference is negative.

$$m_{abs} C_{p_{abs}} \frac{dt_{abs}}{d\theta} = \tau \alpha A_{abs} I \cos \theta + h_{abs} A_{abs} (t_r - t_{abs}) \quad (3)$$

2.2.3. Stove chamber

Stove which is located in lower side of the dryer, is separated from the drying room by using zinc floor. In this subsystem, the heat source is charcoal combustion. Airflow was introduced in order to change the air inside the stove, which provided continuous combustion process. Besides heat penetrates into the drying room through the zinc floor. Part of heat penetrates the stove's wall. The heat balance of this subsystem was therefore:

$$m_{sto} C_{p_{sto}} \frac{dt_{sto}}{d\theta} = \dot{m}_{sto} C_{p_{sto}} (t_{amb} - t_{sto}) + U_f A_f (t_r - t_{sto}) + U_{wf} A_{wf} (t_{amb} - t_{sto}) + q_b \quad (4)$$

2.2.4. Beans

In the beans, surface sensible heat transfer takes place with the drying air while latent heat flows out from the beans incorporating the moisture's motion. The heat balance then expressed as:

$$m_p C_p \frac{dt_p}{d\theta} = h_p A_p (t_r - t_p) - \dot{m}_v h_{fg} \quad (5)$$

for upper beans, solar irradiation after through the drying wall strikes directly on them. The heat balance then expressed as:

$$m_p C_p \frac{dt_{p,up}}{d\theta} = h_p A_p (t_r - t_{p,up}) - \dot{m}_v h_{fg} + (\tau \alpha A)_p I \quad (6)$$

where h_{obs} is heat transfer coefficient calculated for free convection for vertical plate, while h_p is that for spherical body.

Several factors are significantly related to the moisture balance. The moisture to be the most significant source is that produced by the beans. Moisture due to the air flow between the room and surrounding however is certainly significant as well, hence the balance might be expressed as:

$$m_{r,uk} \frac{dH_r}{d\theta} = \dot{m}_{uk} (H_{in} - H_r) + \dot{m}_v \quad (7)$$

The equation employed for this change is expressed as:

$$\frac{dM}{d\theta} = \sum_{n=1}^{\infty} -\beta_n^2 \frac{D}{a^2} \frac{6Bi^2 \exp(-\beta_n^2 D\theta / a^2)}{\beta_n^2 \{ \beta_n^2 + Bi(Bi - 1) \}_n} \quad (8)$$

2.3. Period and Location

This research is considered into five stages, which consist of design and construction of the physical model of system, pre-experiment testing, performance testing with and without load, completion and validation of the models and performing simulation and optimization. The first stage will be carried out in Workshop of Agricultural Engineering Department for one month (August, 2001) while the rest stages will be carried out in Laboratory of Heat and Mass Transfer, Agricultural Engineering Department, Institut Pertanian Bogor, from December 2002 until September 2003.

2.4. Materials and Instrument

The measurement instruments utilized comprise:

1. Experimental apparatus: controlled air generating apparatus, solar dryer with rotating rack, deepbed bin system.
2. Measurement instruments: balance, pyranometer, drying oven, thermocouples, anemometer, manometer, pitot tube, data logger and recorder, camera, PC, caliper, digital multimeter, torquemeter, computer interface, analog-to-digital converter, stopwatch. The material tested is fermented cocoa beans.

2.5. Procedure

The procedures include some aspects, which will be observed for each stage are described below.

2.5.1. Construction of controlled air generating-apparatus (CAGA)

Construction of CAGA based on principles developed by several other researchers. Cooling coil and heater is utilized to control the relative humidity, while the heater controls the desired air temperature.

2.5.2. Construction of the solar dryer with rotating rack system

The system consists of cylindrical solar collector chamber and rotating rack, which installed such that its axis is in one line with the center of the collector. Polycarbonate will be used as wall of the chamber while perforated aluminum was employed as the tray. The both ends (top and bottom end) of the rack's axis is mounted to the chamber structure with bearing connections. Electrical motor with transmission system and savonius generator is equipped interchangeably to rotate the rack.

2.5.3. Hardware testing

The controlled air apparatus testing is performed to obtain the feasibility of afterward step of the experiment. Tests on workability of the whole system for rotation velocity and maximum weight capacity are performed as well.

Pre-experiment

Thin layer drying is performed to obtain relation between air velocity and change of moisture content of beans employed the apparatus shown in Fig. 1, which is connected to the drying-chamber. The drying chamber consists of 4 outlets, where each has valve to set the air velocity. A layer of cocoa beans will be put in each outlet and dried in different air velocities for a pair of temperature and RH. In this fashion, internal and external resistance of both moisture and heat transfer of the beans will be defined.

Major Experiment

The solar dryer is located in the exposed area such that solar irradiation can be received sufficiently during the drying days. The cocoa beans to be dried are placed in one layer on each tray. After the stages are accomplished, the driver motor is activated to start the rotating motion of the rack and measurement starts to be performed.

The objective of this stage is to obtain the performance of the system in drying of cocoa beans including the drying time, moisture-content uniformity of the beans, energy consumption and quality of drying result. For these purposes, the following parameters will be observed:

- Beans: a) moisture content b) number of broken beans; e) fat content;. Point (a) is observed by virtue of weighing periodically the bean's sample (every 1 hour) and finding the dry weight at the final of the experiment. Points (b) and (g) is measured

for 10 times during the drying process. The rest points are observed after the drying process is accomplished.

- Movement mechanism: a) torque and b) electrical quantities of the motor: voltage and current.

2.5.4. Modeling and Computation

The equations are solved simultaneously using numerical method of *Predictor-Corrector finite difference* with Adams-Moulton method. Since this method used three terms of time derivative, the first three terms are calculated by Runge-Kutta method. Simulation is conducted under Visual Basic 6.0 programming language. Several functions need to be created for convenient computations. This is performed since several parameters are dependent on change of temperature and humidity. In addition, derivatives of some functions are required in the computations, such as those of absolute humidity and dew-point temperature. Moreover, the calculation of constant drying rate, which is analogue to that of free water surface, has to be performed using iterative method (Newton-Raphson iteration). Model validation was performed by comparing the air temperature and humidity as well as beans' moisture content change of calculation result to those of measurement data using APD and COD.

2.5.5. Scenario used in the simulation

Drying process in batch mode is an unsteady state case. It can be expected that the required energy for drying process will be decreased as the moisture content is reduced. By controlling the air at relatively constant condition, the energy required for heating and airflow will be reduced gradually. In order to obtain that reduction, fuzzy logic controlling was applied. Three scenarios tested are displayed in Table 1 including scenario VI – VIII.

Table 1. Scenario used in drying process

Scenario	Load (kg)	Conditions
I	125	<ul style="list-style-type: none"> ○ Drying is performed only at day time ○ Combustion rate of 0.375 kg/h ○ Air mass flow rate of 0.1 kg/s
II	125	<ul style="list-style-type: none"> ○ Drying is performed at day and night time ○ Combustion rate of 0.375 kg/h ○ Air mass flow rate of 0.1 kg/s
III	125	<ul style="list-style-type: none"> ○ Drying is performed only at day time ○ Combustion rate of 0.75 kg/h ○ Air mass flow rate of 0.1 kg/s
IV	125	<ul style="list-style-type: none"> ○ Drying is performed at day and night time ○ Combustion rate of 0.75 kg/h ○ Air mass flow rate of 0.1 kg/s
V	500	<ul style="list-style-type: none"> ○ Drying is performed only at day time ○ Combustion rate of 1.5 kg/h ○ Air mass flow rate of 0.4 kg/s
VI	500	<ul style="list-style-type: none"> ○ Drying is performed continuously ○ Fuzzy logic controlling at set point: <ul style="list-style-type: none"> ○ Air temperature: 55°C ○ RH: 35%

VII	500	<ul style="list-style-type: none">○ Drying is performed only at day time○ Fuzzy logic controlling at set point:<ul style="list-style-type: none">○ Air temperature: 45°C○ RH: 50%
VIII	500	<ul style="list-style-type: none">○ Drying is performed only at day time○ Fuzzy logic controlling at set point:<ul style="list-style-type: none">○ Air temperature: 40°C○ RH: 70%

3. RESULT

3.1. Drying Kinetics of Cocoa Beans

Thin-layer-drying experiments of eight air conditions have been run using the apparatus shown in Fig 1. The results show that drying air velocity has a significant effect in initial periods. The influence, however, will be reduced in the subsequently periods.

It is obviously appeared that temperature of drying air significantly influence the drying rate (Fig 2). As the temperature is higher, drying rate for all periods increases as well. It has been recognized that drying temperature will increase the diffusivity both internal and surface. In addition, vapor pressure inside the beans increases as the temperature become higher. This means that driving force of moisture motion, i.e. the difference of vapor pressure inside and outside the bean, increases as well. As a result, rate of moisture transport increase and drying time in which the moisture content reach the equilibrium became more rapid.

The air motion will alter the moisture boundary layer became thinner, hence the concentration difference of the concentration per distance unit increase. Therefore, this phenomenon occurs when the moisture on the surface is still in sufficient amount. This hypothesis is supported by indication of appearance of air velocity having strong effect in initial period than the rest. It may be seen as well that the curves finally coincide at the moisture contents of about 60 %d.b. This shows that below the value, drying air velocity does not affect the drying rate any longer. In addition, the figure shown that in lower drying temperature, effect of air velocity on the decreasing rate of moisture content is more significant than that under higher temperature.



Fig. 1. The Controlled Air Generating Device

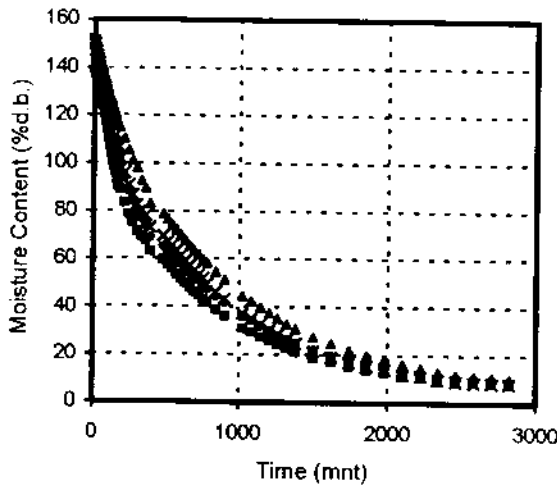


Figure 2. Moisture change vs time for various drying air velocities at $T = 38^{\circ}\text{C}$

Polynomial equations were employed to develop relations between the transport properties and the air conditions. Since the air conditions simultaneously influence the properties, multiple regressions method was used. The equation for drying constant K is as follow:

$$K = 3.73 \times 10^{-5}T - 2.2 \times 10^{-7}T^2 - 2.55 \times 10^{-3}HV + 5.94 \times 10^{-5}V - 0.00089 \quad (10)$$

while for surface mass transfer coefficient:

$$Bi \times K = 1.21 \times 10^{-4}T + 3.62 \times 10^{-4}V - 5.35 \times 10^{-8}T^2V^2 + 1.27 \times 10^{-6}H^2 - 0.00524 \quad (11)$$

and for Me :

$$Me = -0.830T - 1269H + 32.931TH - 2.674T^2H^2 + 40.787 \quad (12)$$

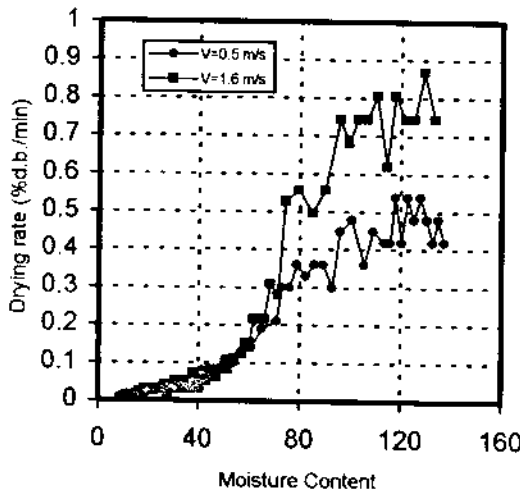


Figure 3. Drying rate vs moisture content for various drying air velocities at $T = 45^{\circ}\text{C}$ and $H = 0.038$

3.2. Solar Drying

3.2.1. The construction of the solar dryer

The solar dryer that has been constructed is shown in Fig 4. The dryer has four main components, which are transparent wall, rotating rack, blackened plate with half-cylinder shell shape and driving motor or savonius generator. Polycarbonate sheet is implemented as the chamber wall, while the hole-iron as the frame. Perforated aluminum sheet is used as the rotating rack, which is mounted to the iron pipe as the rotating-axle such that the tray perimeter and the dryer wall has a uniform space in radial direction. This arrangement makes the rack and the wall act as an axial blower. While air outlet is positioned at the center-top of the dryer, the inlet is located at the bottom encircle the dryer wall. This arrangement is subjected to assist the airflow with the free-convective flow.



Fig. 4. The solar dryer

3.2.2. Experimental Results

3.2.2.1. Ambient condition during the experiment

Experiment on drying performance testing is performed in May 2003 – July 2003. Pyranometer was used to measure the solar irradiation, so the irradiation is composed of diffuse and direct irradiation or usually specified as the global irradiation.

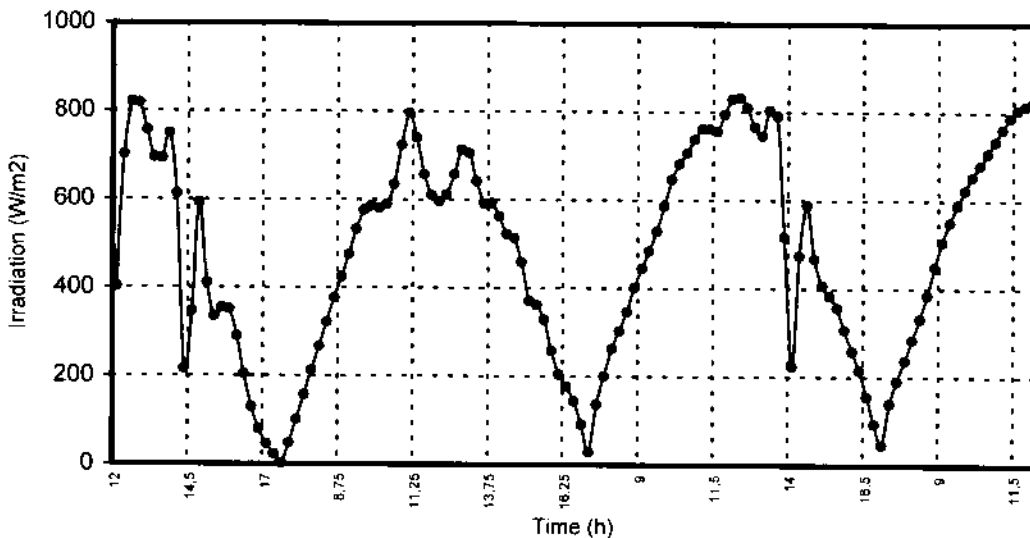


Fig 5. Fluctuation of Solar Irradiation during the Experiment I

The average of daily total irradiation on the first experiment is 494 W/m², which is slightly lower than the average of total irradiation in Indonesia (562.5 W/m² or 4.5 kWh/m² for sunshine duration of 8 hours).

3.2.2.2. Temperature and RH of Drying Air

As mentioned before, the solar dryer employs the solar irradiation and charcoal combustion as the heating source. Since no control applied in this dryer, the drying air temperature fluctuates as the power of heating source does as well. The range of temperature and RH of drying air for all experiments is presented in Table 2. Experiment 2 experienced the highest of drying air temperature, while the lowest in experiment 1.

Table 2. Drying air during the experiments

		Experiment		
		I	II	III
Temperature (°C)	Average	39.5	40.4	40.9
	Minimum	24	27.3	28.3
	Maximum	58	54.4	56.9
Relative Humidity (%)	Average	61.1	61.6	58.4
	Minimum	29.3	33.6	29.7
	Maximum	86.2	88.8	96

The ambient and drying air difference average for each of the three experiments was 7.2°C, 6.9°C and 9.1°C, respectively. It can be observed that the three experiments have the differences that are relatively equal but the experiment III has the highest value. Amount of additional heating consumption (i.e. charcoal combustion rate) might be the dominant factor, which is responsible for the differences. In addition, magnitude of solar irradiation must contribute insignificantly, since it increased both the ambient as well as the drying air. However it is important to notice that the effectiveness of air-beans contact is very influence the conditions.

Roughly, Fig. 6 shows that the magnitude of drying rates for the three experiments are approximately equal. Drying at night-time only use the charcoal combustion as the heating source, which is located in the bottom of the chamber. It will be seen in the next chapter that drying rate is relatively low in the upper part of the chamber. Therefore, an equivalent energy to this experiment would be used as not effective as the other experiments.

In general, drying rate in this study is higher than that of the previous study by the author on cocoa beans solar drying (Nelwan, 1997). In that study, vibrating rack was used as the beans' container. Although the heating source used was higher, air-beans contact might not as effective as in this study. Drying time required in one testing of the study was 39 hrs to reduce moisture content from 65% d.b. to 7.1% d.b compared to this study which was 37.7 h from 150% d.b. to 7.9 % d.b. The improper air-beans contact might be occurred due to the absence of blower utilization.

Although the average drying rate in this study was lower than that in Manalu's (1999) experiment, the initial drying rate in this study was surprisingly higher. This is perhaps related to the bed arrangement in both drying experiments. Deep bed arrangement provides accumulation of the pulp and hence in the initial period the air experienced resistance resulted from it. After some times, as the pulp dried, the resistance decreased and the drying rate even became higher than this experiment.

3.2.2.3. Torque and rotating power requirement

The average torque requirement to rotate the rack for various loads is presented in Table 3. The load of 0 kg means that the load rotated is only the weight of the rack itself. It can be expected that the average torque was larger as the load was higher. This was due to the friction force, which is proportional to the weight of the load, especially in the initial movement.

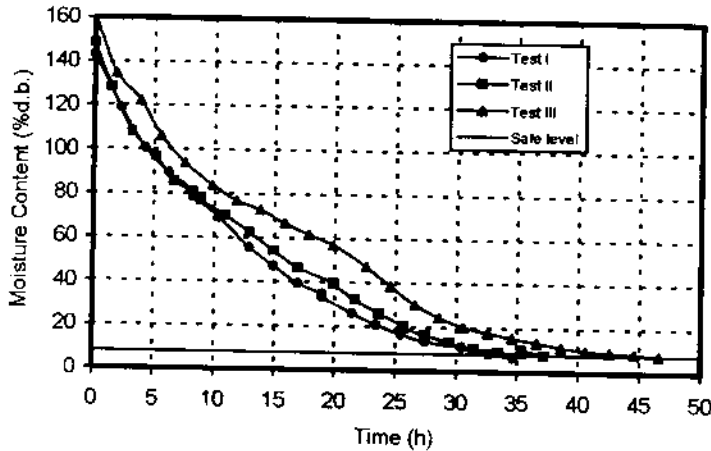


Fig. 6. Curve of decrease of moisture content

Table 3. The average torque and power requirement

Load (kg)	Torque (N-m)	Power (W)
0	6.4	18.6
50	7.8	22.8
90	9.5	27.8
120	10.2	29.9

The angular velocities for all loads were uniform and constant (which was 2.88 rad/s). The power requirement is obtained by multiplying the corresponding torque to the angular velocity. The trends showed are agreed with that of net electrical power measurement – measured as the motor's power difference of installed and uninstalled to the rack –, which were 55 W and 88 W for load of 0 and 120 kg, respectively.

In general, although the average torque was high, the required power was relatively low. The low angular velocity caused this fact. Higher power was required only in initial period of rotation.

3.2.2.4. Quality of the dried beans

Table 4 summarizes several parameters of dried beans quality as the general conditions. The parameters showed that the dried beans had an acceptable quality for trading intensions. However, in order to classify the quality, several parameters such as presented in Table 5 should be determined. It is observed that the pH of the beans for all experiments is higher than the minimum recommended. Meanwhile, the free fatty acid of the beans is much lower than the maximum recommended.

Experiment I had the highest free fatty acids while the lowest was in experiment III. In experiment III the drying process, which was conducted continuously, was probably

reduced the beans lower than the other experiments during their initial period. Therefore, opportunity for chemical reaction and microbiological activities, which produce the free fatty acid, can be reduced.

Table 4. Parameters of quality general conditions

No.	Test	Conditions		
		I	II	III
1.	Life insect (-)	not exist	not exist	not exist
2.	Dead insect (-)	not exist	not exist	not exist
3.	Moisture content (% w/w)	6.3	7.3	7.3
4.	Smoky and/or abnormal and/or foreign flavor (-)	not exist	not exist	not exist
5.	Content of broken beans and/or beans fracture and/or seedcoat fracture (%w/w)	1.4	0.8	2.3
6.	Foreign matter content (% w/w)	0	0	0

Table 5. Parameters of quality particular conditions

No.	Test	Conditions		
		I	II	III
1.	Number of beans per 100 g	118	116	123
2.	Moldy beans (beans/beans)	3	0	1
3.	Unfermented beans (beans/beans)			
	• Slaty beans, White/purple beans	22	14	19
	• Violet beans	14	9	4
4.	Insect infected beans (beans/beans)	0	0	0
5.	Germed-flattened Beans (beans/beans)	12	12	16

Table 6. Parameters of quality of recommendation

No.	Test	Conditions		
		I	II	III
1.	Total fat content	38.7	30.9	32.4
2.	pH	5.63	5.53	5.91
3.	Free fatty acid	0.75	0.70	0.56

3.3. Input Energy

Total of utilization of all the three of energy sources, which are used for each of the experiments is presented in Fig. 7. Availability of solar irradiation, which fluctuates according to the weather condition and time (hour in the day and day in the year), cause the additional heating source is required in order to keep the air temperature and humidity in an adequate condition during the drying process.

In this experiment, additional heating consumption was set according to the ambient condition and the beans being dried during the process. Therefore, the amount of those that was consumed was varied to each of the experiments as well as to the drying time, where in general there was a significant difference between day and night time process. In addition, the duration of the process certainly caused the difference of total consumption of the heating source for each of the experiments.

The electrical energy consumption was certainly invariable, since the rotation of the rack and fan were constant. As a result, this energy consumption was only depended on the duration of the effective process. It is clearly then, that experiment III consumed the highest electrical energy, while experiment I the lowest.

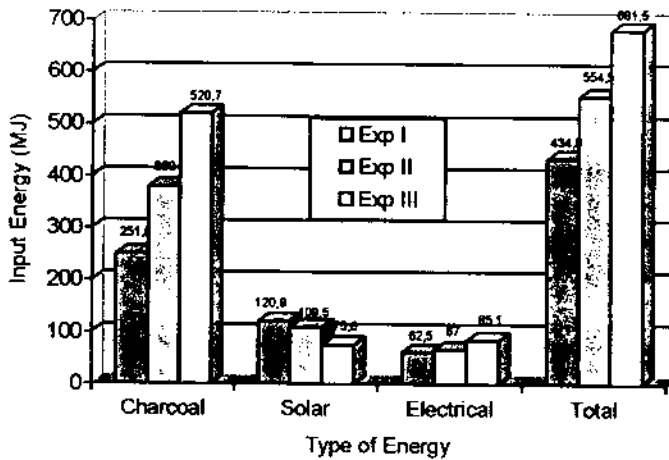


Fig. 7. Energy input during drying

The energy produced by solar irradiation and charcoal combustion was employed for air heating. Then, the energy was used to heat the cocoa beans and to vaporize moisture from the beans.

As stated before, all of the electrical energy is utilized to move the rack and the blower (as mechanical energy source). Table 7 presents that the ratio mechanical energy to the total energy is low. Such a result was also found in the previous researches (Manalu, 1999; Nelwan, 1997).

Table 7. Percentage of each of the components of energy input

Component	Portion of each component (%)		
	I	II	III
Charcoal	58	68	76
Solar	28	20	11
Electrical	14	12	13
Total	100	100	100

3.3.1. Efficiency of energy consumption

3.3.1.1. Specific energy consumption

The specific energy consumption (SEC) in all of the experiments are displayed in Fig. 8. It is observed that the experiment II has the lowest value. This fact is unsurprising since although the energy input during the experiment was not the lowest, the amount of moisture that had been evaporated was sufficiently large (i.e. 70.8 kg). In contrast, the experiment III had the largest SEC. Apparently, drying in night time provide a disadvantage in energy consumption. There are at least two reasons, which cause this condition. Firstly, this experiment had only a little of tempering period. It was observed in the section II that in tempering period the moisture content of the beans also decrease without heating source. Hence, in the experiment-I and II, the source consumption was saved for several percent of moisture reduction. Secondly, since the process duration in nighttime in which the temperature is relatively low in the

experiment was longer than the rest, the drying rate was low as well. In the experiment I, although the energy input is the lowest, the amount of product being dried is not as large as the other experiments.

Nelwan (1997) obtained that the specific value ranged from 12.5 MJ/kg to 24 MJ/kg using the vibrating rack as the chamber, while a range of 6.2 to 7.9 was observed in deepbed drying experiment performed by Manalu (1999). However, calculation in this study differed from both of the previous studies. If in this study the calculation was performed such as in both studies, the result is significantly lower, which are 6.9, 6.3 and 7.9 MJ/kg. Obviously, that the SEC is approximately equal to that of Manalu (1999).

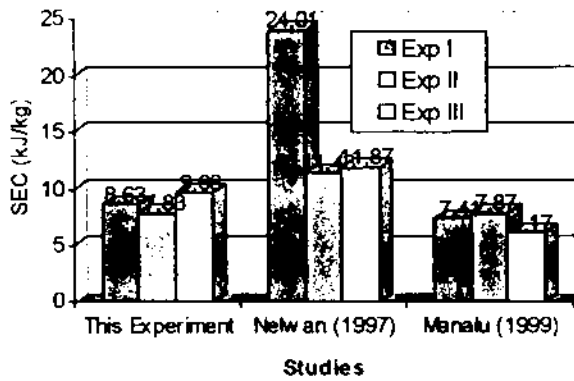


Fig. 8. Specific Energy consumption in this study and in several previous studies

It is worthwhile to notice that in this experiment, a heat exchanger (i.e. zinc floor) was used, while the both of previous studies used a direct heating. It is reasonable that if a dryer (or generally a device) employ a heat exchanger, energy that is required will be higher than those (if possible) without it. However, in this study the dryer still has SEC approximately equal to that of Manalu (1999), and even consumed energy greatly lower than that in Nelwan (1997). Therefore, it can be concluded that in this dryer system, the drying air had been used properly to dry the beans.

3.3.1.2. Thermal Efficiency (TE)

Equation (4.3) is employed in order to obtain the thermal efficiency of the dryer. As the SEC, TE is a ratio of energy consumption in a dryer, however both the nominator and denominator of the ratio is expressed in energy unit, then percentage usually used as the expression of the value. TE has a range from 27.2 % in experiment III to 33.7 in experiment II. In addition, it is obvious that the values must be in reverse order to the SEC.

According to Hall (1957), a typical of corn dryer using oil-fired direct heater had an efficiency up to 34.6%. The value is approximately equal to this study's result especially in Experiment I and II. Harsono (1997) obtained that in drying of cocoa beans using a dryer of tunnel type, the TE is about 20.2 – 22.2 % for a load of 2061-2188 kg. This dryer used wood as the fuel. Several other experiments on drying of cocoa beans conducted in IPB showed lower thermal efficiencies, for instance: Suriyanto (1991) obtained about 2.8 – 7 % for solar tunnel drying; Wikri (1998) obtained about 13.4 – 20.6 % for tray drying using coal as the fuel; Cahyana (1989) obtained efficiency of 0.87 – 7.21 % for tray drying using kerosene as the fuel.

3.4. Calculated and measured parameters

3.4.1. Model validation

Change of air temperature to drying time is described in Fig. 9 for experiment II. It is observed that temperature fluctuated during the process. Charcoal, which was used as the fuel, was fed in batch mode. Therefore, it can be observed that the combustion rate's curve increased and decreased periodically during the process. The combustion rate's rise was observed when the charcoal just started to be burned. After a moment (± 30 minutes) the charcoal amount reduced, and certainly the combustion's rate. On the other hand, solar irradiation fluctuated due to the weather condition and certainly, the solar time.

Nevertheless, the temperature tended to increase although the solar irradiation and combustion rate were fluctuated in relatively constant range. At first day of both experiments, temperature was around 35 – 40°C. However, after about 15 hrs (i.e. moisture content of 60% d.b.) the temperature increased. The heat content of air that was used to evaporate moisture from the beans at initial stage was much greater than the rest period. Although the enthalpy of air was approximately constant, in that period latent heat dominate the components of the enthalpy. Sensible heat, which is represented by the air temperature, was inferior. However, when the beans began to dry, the amount of moisture evaporated had been reduced. Consequently, latent heat became lower and sensible heat dominated the enthalpy of air. This was indicated by the rise of temperature.

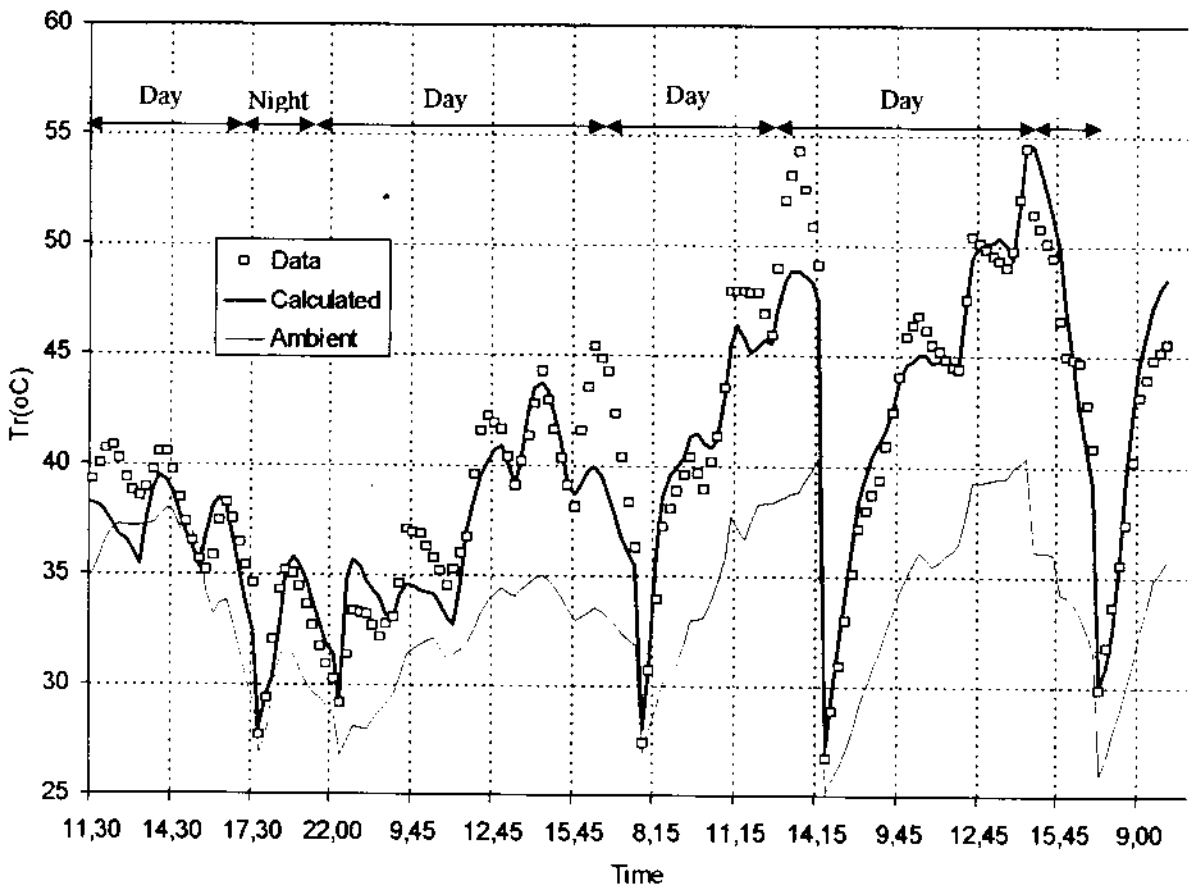


Fig. 9. Comparison of measured and calculated temperature change in Experiment II

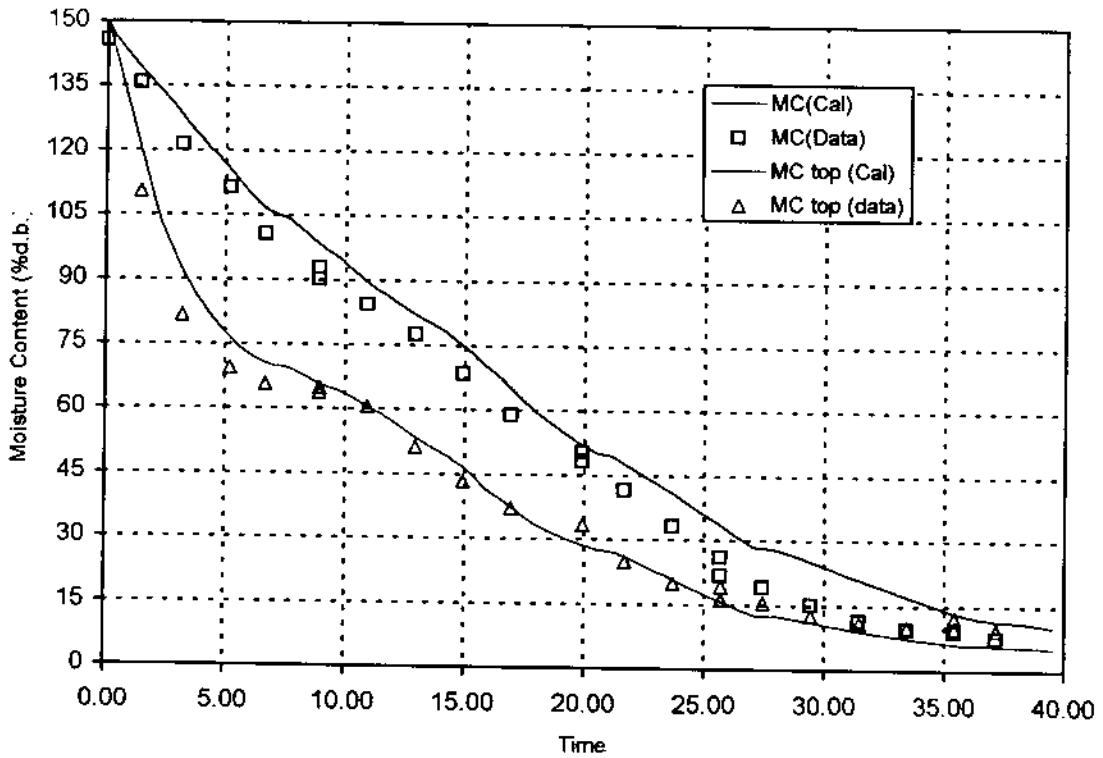


Fig. 10. Comparison of measured and calculated moisture change in Experiment II

3.4.2. Simulation result

In the scenario used in the simulation, the total solar irradiation was 4.5 kWh/m², which is approximately same to that of Indonesia. The data were obtained from Prasetyo (1996) in Jember for one day from 8.00 to 16.00

Fuzzy logic controlling at temperature of 55°C and RH of 35% (scenario VI) reduced the drying time significantly. This can be seen by comparing scenario V and VI. The drying time had reduced from 38 hours (in scenario V) to 16.5 hours (in scenario VI) as the controlling was applied. This drying time is approximately equal to that of laboratory's result (Chapter II at air condition 21). It is interesting to notify that the moisture content has reduced to its half by 5 hours drying. Setting the temperature of 45°C and RH of 50% (scenario VII) provided drying time of 26 hours, while scenario VIII (40°C and RH of 70%) provided 39 hours. At the final stage, the temperature of drying air would be allowed to be higher than the set point. This is especially when the heat from combustion is not required anymore and the heat is merely available from irradiation. This is also an advantage since the higher temperature accelerates the drying rate.

The fuzzy logic was performed by adjusting the combustion rate and air mass flow rate during the drying process. In the initial period, the combustion rate to increase the air temperature was very large, since most of heat was absorbed to evaporate the beans' moisture. Meanwhile, more airflow rate was required to discharge the moisture inside the drying room. Entering the middle of the drying process, the amount of moisture evaporated to the drying room had reduced, and then it was not necessary to keep any longer the same level of combustion rate and air mass flow rate. By reducing the air mass flow rate, the heat loss corresponding to the air flow was reduced.

Figure 11 shows the change of the combustion rates of the three scenarios, while Figure 12 displays the change of airflow rate. The initial combustion rate of the scenario VI reaches 12 kg/h, while scenario VII and VIII are 7 kg/h and 3 kg/h, respectively. This rate gradually decreased to zero, where the moisture content was small enough. This was clearly observed in scenario VIII, when the drying time had reached more than 33 hours.

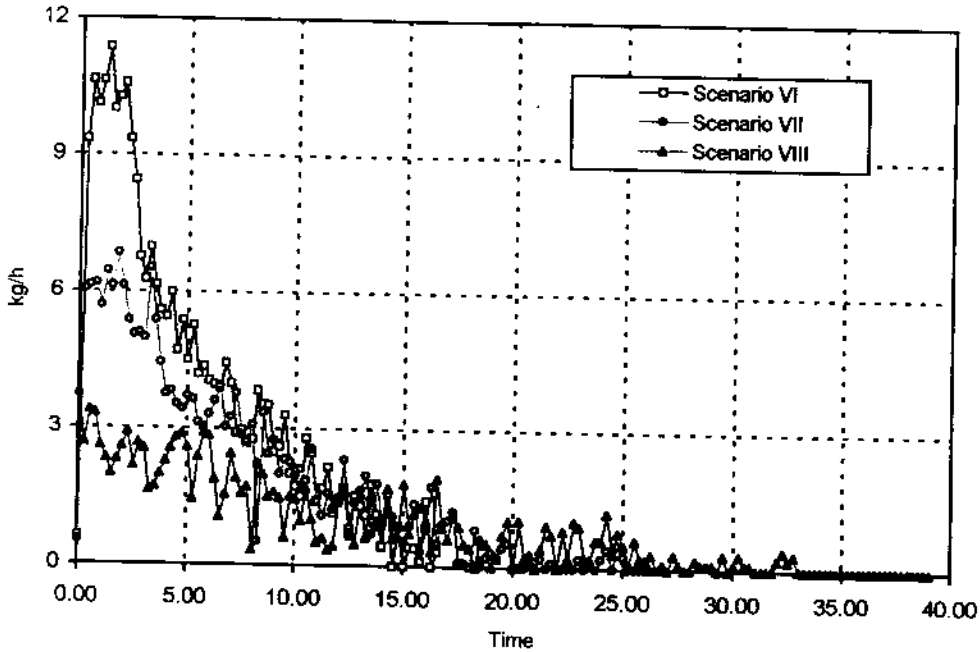


Figure 11. Change of combustion rate for fuzzy logic controlling scenarios

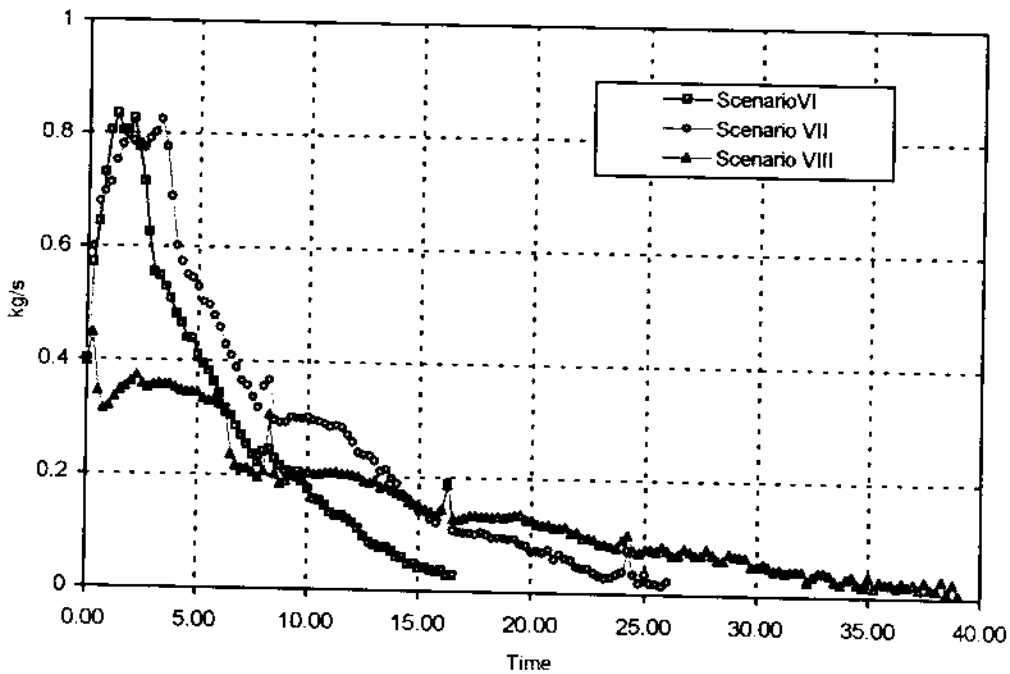


Figure 12. Change of airflow rate for fuzzy logic controlling scenarios

Although the initial combustion rate of Scenario VI was higher than VII, the air flow rate necessary were approximately equal. This was caused by the absolute humidity that should be kept in Scenario VII was lower than in scenario VI. The airflow rate for both scenario ranged from 0.8 kg/s to 0.01 kg/s. Meanwhile, scenario VIII ranged from 0.45 kg/s to 0.01 kg/s.

Thermal energy consumption from solar and charcoal are summarized in Figure 13. Higher combustion rate provides slightly more specific thermal energy consumption. It can be seen by comparing scenario I and II with III and IV. In this perspective, it is better to avoid use of high combustion rate. This is not the only consideration in drying selection, however. Drying time becomes the other important factor in the selection.

However, adjusting both airflow and combustion rate by fuzzy logic controlling during drying process significantly reduces the thermal energy consumption. The reduction almost reaches 50%. The lowest consumption is of scenario VI due to its fastest drying time. Therefore, adjusting the airflow and combustion rate provides effective and efficient heat utilization.

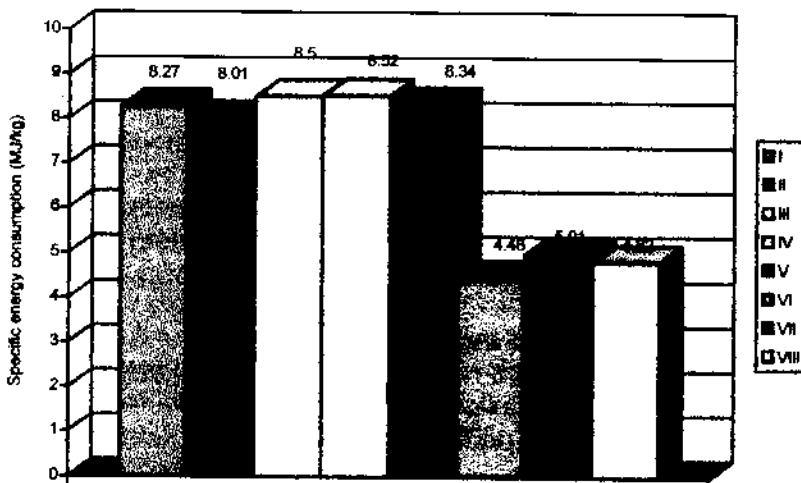


Figure 13. Specific energy consumption of all scenarios

The continuous drying process provides uncertain effect to the heat consumption. At a lower combustion rate (Scenario I and II), continuous drying process reduces the consumption while at higher combustion (Scenario III and IV) the process increases it. This is due to the high solar irradiation during the drying process. In spite of that, the amount of charcoal energy required was significantly reduced. Apparently, the consumption's change depends on the time where the process occurs.

Table 8. Energy input for Scenario VI – Scenario VIII

Source	Energy input, MJ (%)		
	Scenario VI	Scenario VII	Scenario VIII
Solar	174.09 (13.0%)	567.10 (37.3%)	853.18 (57.1%)
Charcoal	1096.76 (82.1%)	859.63 (56.5%)	520.50 (34.8%)
Electricity	65.12 (4.9%)	94.56 (6.2%)	120.49 (8.1%)

Increase of amount of beans being dried apparently did not affect the heat consumption rate (Scenario I and V). Equivalent increase of heat input to the beans being dried causes this fact.

Effort to reduce the consumption of charcoal is evidently available. This can be seen by comparing the scenario VI – VIII, which is described in Table 8. When the set point is fixed at low level (Scenario VIII: 40°C, RH 70%), and drying is conducted in day time only, the charcoal consumption can be saved and then, the solar irradiation is increased. Percentage of the solar irradiation of this scenario was 57.1%. The charcoal energy was reduced from 1096.76 MJ to almost its half, 520.50 MJ. This reduction is equivalent with 1.68 MJ/kg moisture evaporated. This means that the commercial energy consumption was only 2.07 MJ/kg.

3.5. Financial Analysis of the system

One of the main criteria of consumer of the production device is the economical feasibility. The cost and benefit analysis is usually performed to recognize the feasibility. Since transparent material is used in its construction, fixed (i.e. construction) cost solar drying is generally expensive. However operational cost is expected to be low since large portion of the cost (i.e. solar energy) can be obtained at no cost.

Integration of collector and drying chamber of solar drying is a beneficial effort. Construction of greenhouse effect solar dryer, from optimization result, is lower than those with flat plate solar collector (Kamaruddin, 1993). Moreover, Muller *et al* (1990) obtained that total initial cost of greenhouse type dryer is about half of that for a shed, which is usually required as the superstructure for conventional batch dryer.

The simulation result for 500 kg of cocoa beans drying in the Chapter V (Scenario VI and Scenario VIII) was employed in order to obtain the financial prospect of a scaled-up dryer. The component of cost for this scaled up drying is shown in Fig 14. Scenario VI has a short drying time (16 hours), but higher combustion rate (3.93 kg/h), while scenario VIII has 39 hours drying time and 0.80 kg/h.

About 57% of energy consumed by the dryer in Scenario VIII was solar energy. Therefore, the variable cost in this scenario was much lower than the Scenario VI. However, since drying time in Scenario VI is much shorter than the Scenario VIII, number of batch in a year increases. As a result, the fixed cost will be reduced. Total cost for the Scenario VI and Scenario VIII are Rp. 321/kg and Rp. 297/kg, respectively. Operation strategy, therefore, significantly influences the drying cost.

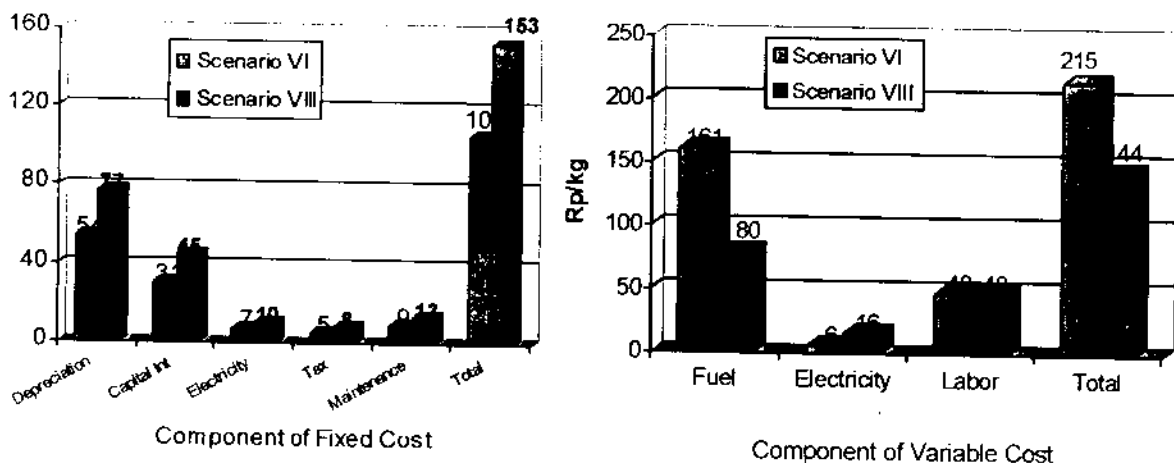


Figure 14. (a) The fixed cost and (b) the variable cost per kg wet beans

As most of dryers or other machines, the depreciation and capital interest's cost are the most dominant components of the fixed cost. These components are representative of the price of the dryer, which is relatively expensive. Aluminum rack, chamber frame, polycarbonate-wall and fans have the highest price compared than the other components.

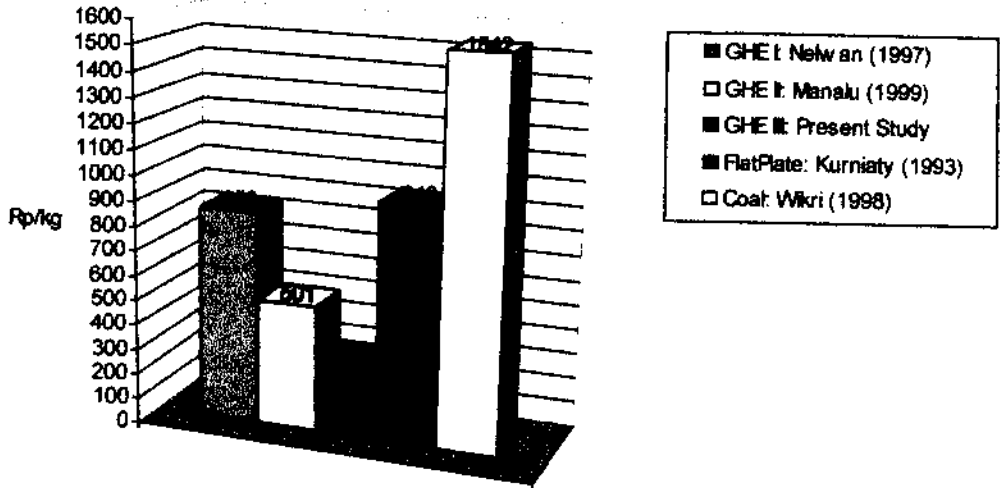


Fig. 15. Comparison of drying costs of several types of dryer

In order to reduce the price, substituting materials are necessary to be employed. For instance, mica plastic is available to substitute the polycarbonate since it has a high radiation-transmittance though its useful life is only about 1 year. In addition, aluminum rack might be substituted by plastic net, yet a bottom support is necessary to hold up the beans. It is also important to keep in mind that when a mass production is applied, the price of the components is normally reduced.

In general, it appears that this solar dryer has a considerable low cost. This becomes more significant, especially when comparing its cost to that of Nelwan (1997). This dryer's cost is still lower than that of Manalu (1999) used deep bed method.

Other studies, such as Kurniaty (1993) found that the drying cost was \$0.11 (Rp. 946) per kg wet beans. The drying capacity was 6 ton of cocoa beans. Meanwhile Wikri (1998) obtained that the drying cost is \$ 0.17 and 0.27 (Rp. 1542 and Rp. 2385) per kg wet-beans for load of 132 – 220 kg wet beans. The dryer used coal as the heat source with indirect utilization of the flue gas.

4. CONCLUSIONS

A GHE type solar dryer with rotating rack has been constructed and tested. The capacity per unit space of the dryer was 60.5 kg/m³ or equal to 55.1 kg/m². Mechanical power for rotating rack of 120 kg load was only 0.088 kW in steady motion.

Thin layer drying experiment showed that although the constant rate period was relatively short (less than 10% of drying time), amount of moisture removed was very large i.e. from about 135-175 % d.b. to 104 %d.b. in average (about one-third of the total moisture). Air velocity significantly influenced the rate during this period. Drying time

from their initial moisture content to 8.1 % d.b. (or 7.5 % w.b.) ranged from 690 minutes to 3180 minutes.

Air-beans contact in the solar dryer has been occurred effectively for continuous as well as intermittent method. This is shown from the following phenomenon: although the temperature was relatively low (39.5 - 40.9 °C), with RH of 61.1-58.4 %, the drying time was relatively short except for continuous experiment (34.7- 46.6 hours). While the temperatures tend to increase as the beans dried, the RH became lower. Comparing to the thin layer drying result, there was still a potency of drying time reduction in the beginning period.

During the tempering, moisture content reduction (desorption process) was still occurred. Although with such the conditions, the general quality of the dried beans obtained was still acceptable for trading purposes. No smoke odors and less than 3% of broken beans had been found.

The SEC for the continuous operation of 125 kg load was 9.88 MJ/kg water evaporated while for intermittent operation of 120 kg load was 7.95 MJ/kg water evaporated.

Lump approach modeling using Finite Difference was much faster than the previous modeling, and produced good correlations with the data including temperature, relative humidity, and moisture content. In addition, the lump model has successfully approached the trend of change of the drying parameters.

Fuzzy logic controlling can improve the SEC, since this method has successfully provided suggestions for effective heat supply and airflow. In addition drying time can be accelerated up to 16 hours with reasonable energy consumption. Low commercial energy consumption up to 2068 kJ/kg was also available by using such the technique.

The scaled-up solar dryer has a considerable low cost, which is Rp. 297/kg – Rp. 321/kg dependent on the operation strategy.

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