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Performance of a Continuous Flow Solar Drying System

Kamaruddin A.*, Uyun A.S.* and Y. Chan+

Abstract – *A continuous flow hybrid ICDC (Integrated Solar-collector-Drying Chamber) solar dryer has been designed and constructed. The proposed dryer then was tested using rough rice with different loading quantity under outdoor conditions. The unique feature of this solar dryer is that it can dry the products simultaneously in three locations within the dryer, namely, within the pneumatic conveyor, within the collector-drying chamber, and above a feed hopper. Experimental results have shown that electric power requirement to transport between 0.5 – 0.7 tons/hr., of rough rice from the feed hopper to the drying chamber was between 500 – 600 W and equivalent to 0.87 W/kg/hr-0.89 W/kg/hr.*

Keywords – pneumatic conveyor, power requirement, rough rice, solar drying, solid-gas pressure drop, specific energy

1. INTRODUCTION

In Indonesia and in most rural areas in the developing countries, direct sun drying has been a common practice to extend shelf life of agricultural products such as food crops, high valued cash crops, forest, animal and marine products. As the climate changing and global warming continue to prevail, direct sun drying may become difficult to perform due to the uncertainty of rainy and cloudy days which can hamper the drying process. Consequently, the unavoidable delay of drying process due to prolonged and unexpected rain fall can result in rapid decomposition of the products and, therefore, not suitable for consumption or for the market. In Indonesia, experiences have shown that using direct sun drying, rough rice with initial moisture content of 26-27% wb, just after harvested, may take days to reach the final moisture content of 14% wb.

Mechanical drying using fossil fuel, on the other hand, has been encountering problems in their application at village level due to the continuing scarcity and high prices of fossil fuels. In addition most of these dryers are imported from overseas making their price unaffordable by local farmers. As a possible alternative, therefore, many researchers have proposed to use solar energy instead of using fossil fuels as the heat source. In such a dryer, solar radiation is utilized in such a way so that the air flow, air temperature and RH are controlled at constant level to achieve faster and even drying process. Modern solar dryer is usually provided with auxiliary heating unit such as biomass stove connected to heat exchanger unit to provide clean hot air. The use of auxiliary heater can make it possible to perform drying process continuously days and night, all year round regardless of the availability of solar radiation.

Up to now, many solar dryers have been developed overseas, but nowadays, some domestic designs are also available. Their practical applications, however, differ from country to country, but the majority of them have been ended as laboratory prototypes or as demonstration models. Many solar dryers introduced to the farmers, have stopped operating due to lack of continuous financial support from the project owners, as the projects are mostly implemented on a short term basis, from 10 months to one year only. Another important reason has been due to lack of access to working capitals and market of processed product.

The main purpose of this paper is to obtain the performance of a novel solar dryer for small size granular materials such as rough rice (paddy).

2. LITERATURE STUDY

Solar dryer for granular materials may be divided into two categories. It may be categorized according to how products are being dried. The first type is solar dryer using stationary drying bin (such as flatbed dryer) or tray [1] where the products are kept stay within a bin or on tray. These types of solar dryer are the most popular and have been widely studied by several workers in the past such as by Imre [2], Müller and Mühlbauer [3], Sharma, *et al.* [4], and many others. Review on their performance and economic benefit have also been done such as by Imre [2], Lütz and Mühlbauer [5].

In Indonesia, solar dryer with flat bed has also been studied in Indonesia by Damardjati *et al.* [6] and Kamaruddin [1]. The problems encountered using this type of dryer are due to the different drying rate at each grain layer, where the fastest drying rates occur at the bottom of the bin where hot air is introduced. As the air flow moves upward across each grain layers its temperature will be decreasing and consequently the drying rate will be decrease. This will result in difference in moisture content of the grains at the top and those at the bottom layer. The thicker the bed depth the greater will be the variation in final moisture content

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of the grains. Another type of solar dryer is those where the products are allowed to move and being mixed continuously using mechanical mixer such as the work of Manalu, [7]), or being mixed and flowing in a rotating drum (Kamaruddin and Nelwan, [8]). A new type of solar dryer has been proposed by Kamaruddin *et al*. [9], where the products are allowed to flow under turbulent manner within a pneumatic conveyor and during free fall in an inclined solar collector-drying chamber. This latter system of solar drying was found to consume less electric power per unit mass flow rate of the commodity. Due to the turbulent and mixing action of the commodity while flowing within the conveyor the drying process could be accomplished faster than the traditional method with more even distribution of final moisture content of the dried product.

3. THE WORKING PRINCIPLE OF THE PROPOSED DRYER

Figure 1 shows the basic design of the proposed recirculation type ICDC (Integrated Solar collector-drying chamber) hybrid solar dryer [9]. Granular materials such as rough rice, soy beans, corn kernels, peppers or even coffee berries are first loaded into a hopper (6). In this newer design, hot air generated from a biomass or gas stove (4) is introduced into the blower inlet (7) and then blown directly into the pneumatic conveyor unit (3), as shown in Figure 2.

From the pneumatic conveyor the grains then transported into an inclined ICDC unit, covered by UV stabilized transparent cover (5) after passing a grain distributor (2). The drying process occurring within the inclined ICDC unit (5) follows almost the same manner as those occurring within the pneumatic conveyor. Ambient air coming from the bottom openings of the ICDC unit is drawn upward by the suction effect of the wind vortex (1) and flow counter currently with the falling grains to perform drying process. As the air flowing across the ICDC unit (5) its temperature increases due to the heating of the solar collector plate which is made of blackened metal sheet. The moisture generated from both the drying process occurring within the pneumatic conveyor and within the ICDC unit is then discharged to the surrounding air through the wind vortex (1), while the falling grains from the ICDC unit (5) are distributed evenly within the hopper (6).

The grains on the top layers of the hopper (6) will receive heat from the incoming solar radiation through the two sides of the transparent louvers (7) to perform drying process and the resulting water vapor will be blown by the passing wind through louver openings (7). As the collected grains within the hopper (6) flow freely down toward the hopper's outlet pipe, located at the bottom section, tempering process will take place releasing the grains from thermal stresses and simultaneously allowing even distribution of moisture to occur within the individual grain.

The similar recirculation process will go on and on until the moisture within the grains will finally reach 14% wb a safety level for long storage time and for milling. One drying cycle may start from the hopper exit (6) then continued after grains enter the pneumatic conveyor (3), and completing the cycle after the grains fall freely across the ICDC unit (5) and back into the top section of the hopper (6).

4. ESTIMATION OF DRYING TIME

When a rough rice grain is undergoing drying process can be regarded as a spherical body (Nishiyama [10]) with radius r (m), and mass diffusivity, Dv (m^2/s), the change in its moisture content M (%db) under constant drying air temperature and RH, can be expressed using the following formula [11], [12], [13].

$$\partial M / \partial t = Dv\{\frac{\partial^2 M}{\partial r^2} + \frac{2}{r}.\frac{\partial M}{\partial r}\} \quad (1)$$

Fig. 1. Schematic diagram of the proposed 2,5 ton maximum capacity 2nd generation of a recirculation type hybrid ICDC solar dryer.

Under the initial condition, at t=0, 0<r<R, M-M_0 and the boundary condition at t>0, and r=R, M=M_e, Equation 1, can be solved to obtain the average moisture content, expressed in a simpler form such as given by Equation 2 below[6].

$$\frac{\overline{M}-M_e}{M_0-M_e}=A\exp(-kt). \qquad (2)$$

Here M_e is the equilibrium moisture content of the grain, in % db, A, the geometric coefficient, (-), t, the unit time, while the mass diffusivity, Dv (m^2/h), can be expressed in terms of a drying constant k, (1/h) such that

$$k=Dv\pi^2/r^2 \qquad (3)$$

Therefore, using Equation 2 and the respective value of parameters, k and Me, and the calculated travel time of the grains within each component of the dryer starting from the hopper exit to the flowing grain within the pneumatic conveyor, and when the grain falling within the incline ICDC unit, respectively, the amount of moisture reduction during each drying cycle and the whole drying process can then be determined.

4.1 Estimation of the Travel Time of the Grains across the Conveyor and the ICDC unit

The traveling time of grains passing across the pneumatic conveyor can be calculated from the known value of mass flow rate, W_P (kg/h), the void ratio, ε (-), and the cross section of the conveying pipe A_P (m^2). The travelling velocity V_P (kg/h) then can be written as in Equation 4 below;

$$V_p=\frac{W_p}{(1-\varepsilon)\rho_p A_p} \qquad (4)$$

For a pipe of length, L_{PC}, (m) of pneumatic conveyor, the time of Travel t_{pc} (hr.) is given by

$$t_{pc}=\frac{L_{pc}}{V_p} \qquad (5)$$

For the case of free fall occurring in the ICDC unit with length, L_d, (m), inclined at θ degree from horizontal, the time of fall t_d (hr.), can be calculated using following relation.

$$t_d=L_d/\sqrt{2gL_d\sin\theta} \qquad (6)$$

4.2 The Tempering Time and Travel Time within the Hopper

The tempering time, t_T (hr.), is the time required by the grains to fall due to gravity force within the hopper. It can be estimated by establishing a mass balance within the hopper using Figure 2, such that:

$$A_p dH_h/dt=-A_1C_1\sqrt{2gH_h} \qquad (7)$$

Here C_1 is the discharge coefficient (-), A_P ,the cross section area of the top grain layer (m^2) at any height, H_h, (m), of the grain column within the hopper, A_1 is the cross sectional area of the connecting pipe to the pneumatic conveyor (m^2) and g, the gravitational forces (m^2/s). The integration of Equation 8 will give the following results after some rearrangements and the value of the discharge coefficient, C_1, can be determined from the experiment by measuring the time to discharge of grains at appropriate column height.

$$t_T=-\frac{2}{C_1\sqrt{2g}}\left(\frac{A_p}{A_1}\right)H_h^{0.5} \qquad (8)$$

Here

$$H_h=2W_p/\rho_p A_p \qquad (9)$$

5. THE EXPERIMENTS

There were two types of experiments conducted. The first test was using experimental set up shown in Figure 2, was aimed to determine the two-phase solid-gas pressure drop, power requirement of the blower unit of the pneumatic conveyor and simultaneously determine the drying constant, k and the equilibrium moisture content Me as given by Equation 2.

The second test was using the complete system of the 2nd generation recirculation type hybrid ICDC solar dryer was conducted under outdoor climatic condition heated by both solar radiation and by the auxiliary heating unit. This second test was used to confirm the results of the first test regarding power requirement for the pneumatic conveyor, effect of tempering and to determine the overall drying performance of the system which occurs simultaneously across the pneumatic conveyor, and within the ICDC unit. During the calculation, the effect of additional drying occurring on the top of the hopper was neglected.

5.1 Power Requirement and Drying Test of the Pneumatic Conveyor

Figure 3 show the experimental set up to measure the two-phase pressure drops, drying process and power requirement of the pneumatic conveyor. The apparatus comprises of a centrifugal blower (1) (with 90 degree blade angle) connected to 0.37 m long with 2.5” diameter blower pipe enclosed by a 4” pneumatic conveyor pipe a grain supply hopper (2). The blower pipe was connected to a 4” diameter 5.44 m long pneumatic conveyor pipe (3) inclined at 60 degrees from the horizontal. Along the 3 m length of the conveyor was enclosed with a 8” steel pipe enclosure to function as the shell side of a shell and tube heat exchanger. During drying, hot air generated from an electric heater was forced into the shell side to perform drying process within the pneumatic conveyor pipe. The shell side pipe was wrapped with glass wool covered with an aluminum sheet to reduce heat loss during the heating experiment. At the end of the conveyor pipe a receiving hopper (7) was placed on a digital balance to determine the mass flow rate of the grains. The carrying air flow rates were measured using LT Lutron anemometer with the smallest reading of 0.1 m/s (0.8-30 m/s range) at pipe outlet and at blower intake valve.

Before conducting the drying test, a series of testing was conducted using a transparent 4" acrylic containing air both with and without grains to study the flow pattern, particularly in estimating the void ratio, □, to measure air flow rate at different openings of the blower inlet valves and the resulting pressure drops. A centrifugal blower (model CZR-900) with 900 Watt and maximum capacity with 2840 RPM was used to deliver air at 1320 m^3/h. The external blade radius of the blower was 16.5 cm and width of 3.5 cm, with tangential angle of the blade, β_2 = 90°. Two pressure taps connected to a U-tube manometer (8) were placed at a certain distance from inlet and out let of the 3 m long of the conveyor pipe to measure the two-phase pressure drop. During the performance test of the blower, only air was allowed to flow through the pneumatic conveyor at different flow rate by adjusting the air intake valve. The air flow rate was measured using the LT Lutron anemometer while U-tube manometer readings were recorded after a steady state condition was obtained. A volt and ampere meter (smallest reading of 0. 1 scale each) was place within a switch gear box (5) to measure the required power of the blower.

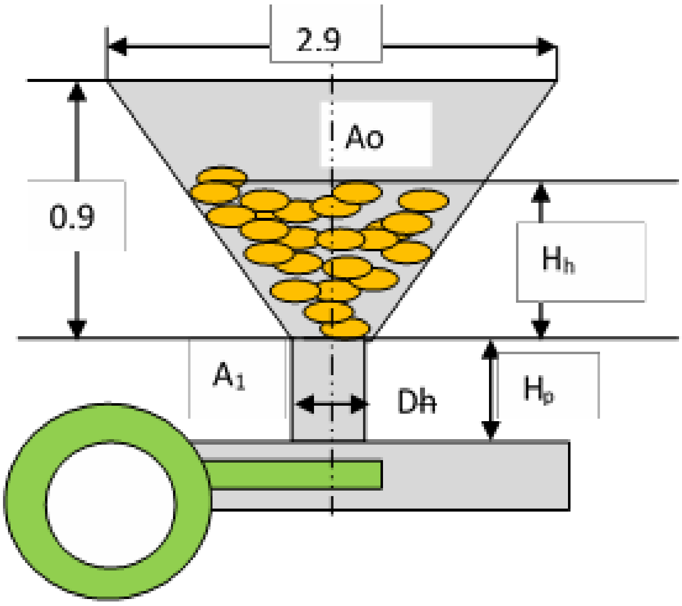

Fig. 2. Schematic diagram of the hopper for determining the discharge coefficient C_1 and the tempering time t_T.

Fig. 1. Experimental set up to measure power requirement of a pneumatic conveyor, and the drying process occurring within the conveyor.

During the drying test to measure moisture reduction occurring across the pneumatic conveyor, a concentric steel cylinder (shell) 8" in diameter was used as heat exchanger enclosing the 3 m long and 4" diameter steel pneumatic conveyor pipe through which hot air was supplied from an electric heater box. The outer wall of the enclosure (shell) was covered with glass wool to prevent heat loss to the surrounding air. CC thermocouple wire junction with 0.3 mm. in diameter was imbedded both at the inlet and out let pipe walls of the conveyor pipes as well as at the inlet and out let walls of the enclosure cylinder (shell). The temperature was recorded using an electronic portable data logger connected to an automatic data acquisition system (6). A digital balance (0.1 kg) and a stop watch was used to measure the mass flow rates of the grains, while the pressure taps and U-tube manometer (smallest reading of 1 mm) were used to measure the resulting pressure drops during each experimental runs.

Before filling the feed hopper (2) with grains, the blower was turned on to supply hot air from the heater box to the conveyor pipe as well as to the enclosing pipe at the same time until a steady state condition was achieved.

The drying test then was conducted by first taking some samples from the tested grains, to determine the initial moisture content using a Kett moisture tester. After that the grains were filled into a grain feeder or supply hopper. The grains then were allowed to fall freely into the pneumatic conveyor pipe located just below the grain supply hopper outlet. After reaching the conveyor pipe end, the grains were collected using a receiving hopper placed on a digital balance. The required time for each 2 kg collected grains was measured using a stop watch and some samples were collected for moisture content measurement. These grains than were filled again to the grain supply hopper to proceed with the next drying process until adequate data have been collected. During each test, the measured data from each sensor were recorded, respectively, to obtain data of air flow rate and mass flow rate of rough rice, pressure drops and power consumption.

5.2 Drying Performance Test of a Complete System of a Recirculation type Hybrid ICDC Solar Dryer

5.2.1. The Drying Test

The complete system of the recirculation type hybrid ICDC solar dryer shown in Figure 1, was tested under the outdoor condition. Newly harvested rough rice grains were obtained from the nearby farm. Before each experimental runs all cc-thermocouple temperature sensors were placed each at both the inlet and out let of the pneumatic conveyor and the shell side, and at inlet and out let of the ICDC unit. The digital RH and temperature meter was used to measure the RH and temperature of the environment and the air above the hopper. Beside the existing pressure taps additional pressure taps were also place at the conveyor pipe bends all connected to a U-tube manometer to measure the occurring two-phase pressure drops during each drying test runs. In addition, a digital solar pyranometer was used to measure global solar irradiation during each experimental runs. Volt and Ampere meters were used to measure the power required and the energy consumed in kWh, during the experiments.

During the drying test hot air from an auxiliary heating unit using gas stove was supplied directly into the blower inlet and on into the pneumatic conveyor pipe which later were used to heat and transport the falling grains into the ICDC compartment. After installing all sensors and recorders, the experiment then was conducted only during day times. Experiment using 200 kg (26 % wb initial moisture) of rough rice grains were conducted by first loading the grains into the hopper through the side wall opening of the dryer.

This first experiment was terminated in the afternoon when the final moisture of the grains has reached 19.8% wb after 4 hrs. 22 minutes of drying time. Using the same grains now become 192 kg, (initial moisture of 19.6% wb) the drying test was continued in the following day. The drying test was started at 11:30 WIST and terminated at 17:45 after the moisture content of the grains have been reduced to 16.3 % wb, with effective drying time of 4 hrs. Since the moisture content of the grains were still high and unsafe for long storage and good milling quality, the drying test was then continued again in the following day for another 3 hrs to reach the final moisture content of 14.8% wb. Therefore, the total drying time was 11 hrs. 22 minutes.

A similar drying test was also conducted using 380.5 kg load with initial moisture content of the grains at 27.1% wb.

5.2.2 Measurement of the Tempering Time

The tempering time was determined from the known height of the grain column within the hopper, and the time required discharging the grains from the hopper using a stop watch. Using 192 kg load, with column height of 0.2 m, the time required was 36.4 second and, therefore, by using Equation 8, the value of C_1 was found to be, C_1=0.00021.

6. EXPERIMENTAL RESULTS

6.1 Pressure Drop and Power Requirement for the Pneumatic Conveyor

Two-phase pressure is one of an important parameter in the designing of the propose recirculation dryer. It is required to estimate power requirement for the pneumatic conveyor. Experimental results have shown that the conveying power requirement was between 0,87 W/kg/h-0.89 W/kg/h for conveying rough rice to 3 m distance with pipes of 4” in diameter with some bends and elbows. The requirement was far less than those reported in the previous studies such as by Hanafi [14] where specific conveying power reported was between 1.75 – 4.1 W/kg/h while from data of commercial pneumatic conveyor was between 1.25-1.5 W/kg/h with total power of between 32-42 kW[14].

Figures 4, 5, and 6, show results of performance test of the 4” pneumatic conveyor with steel pipe. Figure 4 shows the relation between the power, Pw (Watt) and the mass flow rate of the grains, W_p (kg/h), which can be expressed by the following relation.

$$W_p = 1.152Pw + 7.52 \quad (10)$$

Pw, and the ratio of mass flow rate of air and the grains is shown in Figure 5, and their relation is given by Equation 11 below.

$$Pw = 146.12(W_a / W_p) + 366.75 \quad (11)$$

Figure 6, shows the relation, between power, Pw (Watt) and the two phase solid-gas pressure drop per-unit length of pneumatic conveyor pipe. It shows that the power required increased slowly at low pressure drop and began to increase as the pressure drop reached a value above 122.8 N/m^2/m at 560 Watt.

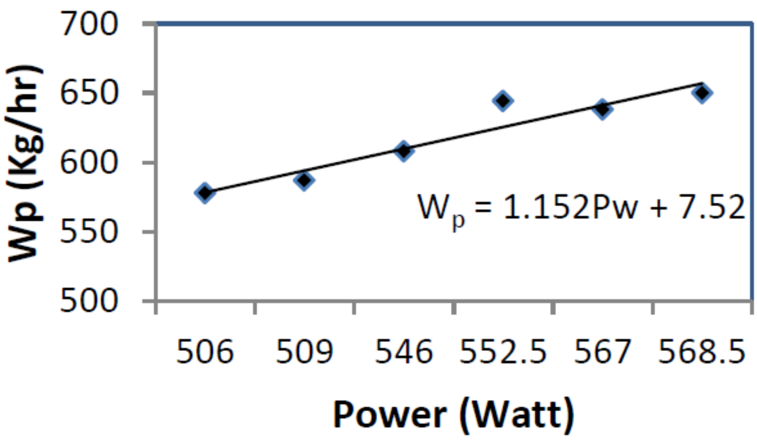

Fig. 4. Relation between power of the blower, Pw, used to drive the pneumatic conveyor and the mass flow rate of rough rice, Wp.

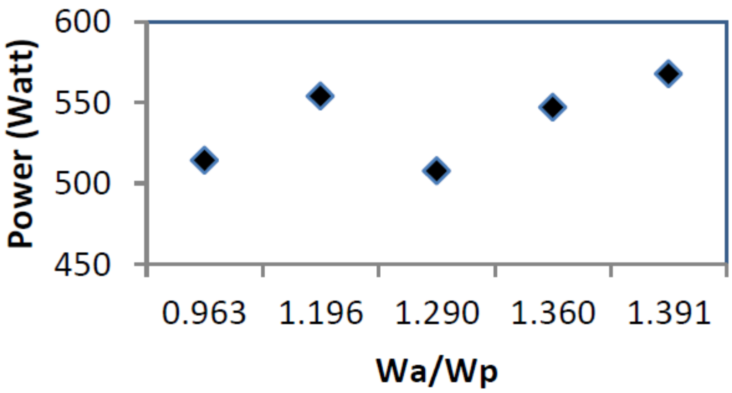

Fig. 5. Relation between power consumption, Pw and γ, the ratio between air, Wa, and grains mass flow rate, Wp.

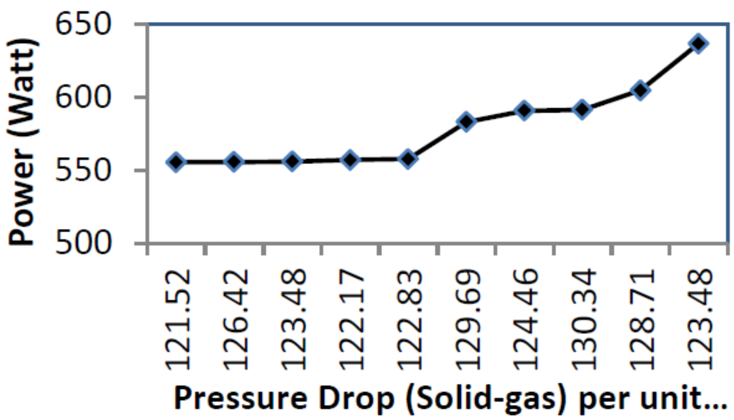

Fig. 6. Relation between two-phase solid-gas pressure drop and power of the pneumatic conveyor.

From a series of experimental runs it was possible to formulate the occurring two-phase pressure drop (Po-P_L) within the pneumatic conveyor using the Ergun type correlation function [12] for packed bed. In this study from a series of experimental runs it was possible to formulate the occurring two-phase pressure drop (Po-P_L) within the pneumatic conveyor using the Ergun type correlation function [12] for packed bed. In this study carrying air (kg/m^3), the resulting correlation can be expressed by:

$$\frac{(P_o - P_L)\rho G}{Go^2} = 0.33\left(\frac{\gamma}{(1-\gamma)}\right)^{-1.77}\left(\frac{D_p}{L}\right)^{0.758}\left(\frac{(1-\mu)}{G_o D_p}\right)^{-1.395} \quad (12)$$

Here P_0 is the static pressure at pipe inlet (N/m^2), P_L (N/m^2), is the static pressure at pipe length L_P,. The parameter γ, is the ratio between mass flow rate of air, Wa (kg/h) and that of rough rice, Wp (kg/h), such that:

$$\gamma = \frac{W_a}{W_p} \quad (13)$$

The comparison between the measured data and calculated results from Equation 12 is shown in Figure 7.

6.2 Drying Process in Pneumatic Conveyor

Figure 8 shows the amount of moisture reduction within the pneumatic conveyor when its inlet temperature was between 33.3°C and 34.6°C and the heated enclosing pipe inlet was between 98.8°C and 120.8°C. Under this condition, the average change in moisture content was 0.511%. These data were collected under the condition when mass flow rate of the grains was between 488 kg/h and 763.68 kg/h, while the electric power consumed was between 540 W and 568.45 W. The largest reduction of moisture content occurred when mass flow rate of the grains was between 540 kg/h-568.45 kg/h. From these data the parameter k, and Me were calculated. The resulting value of the respective drying parameters were k=1.25 (1/h) which is equivalent to Dv=5.07 x 10^{-5} m^2/h, and Me = 6% db as shown in Figure 9 using the method conducted previously by Kamaruddin [1]. These parameters then were used to estimatethe total drying process within the proposed dryer.

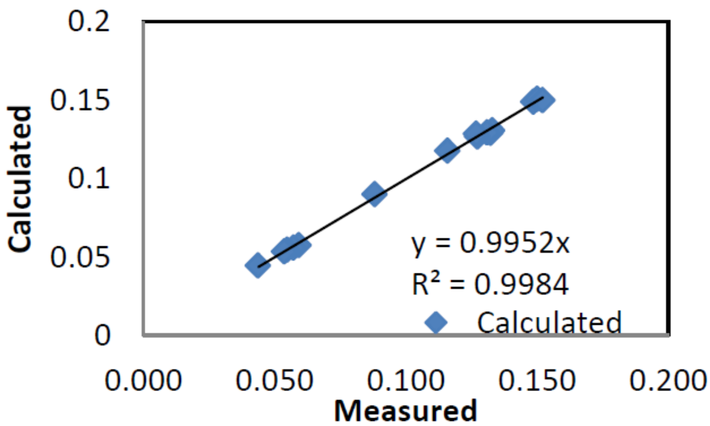

Fig. 2. Comparison between calculated and measured two-phase pressure drop.

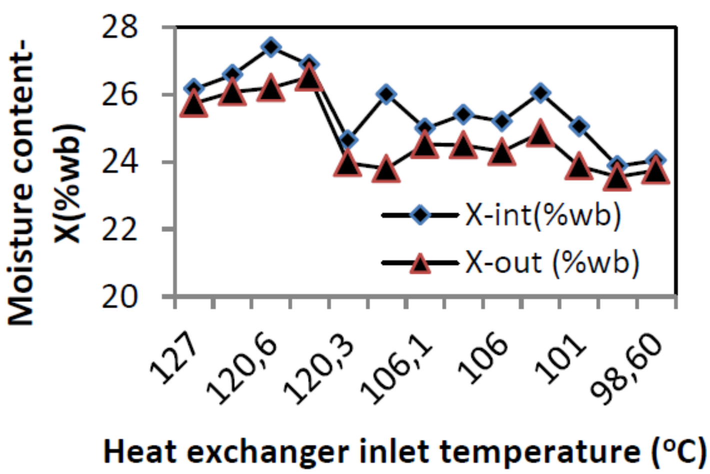

Fig. 8. Change in moisture content from inlet to outlet of pneumatic conveyor where the inlet temperature of the pipe was between 33.3 and 34.6°C.

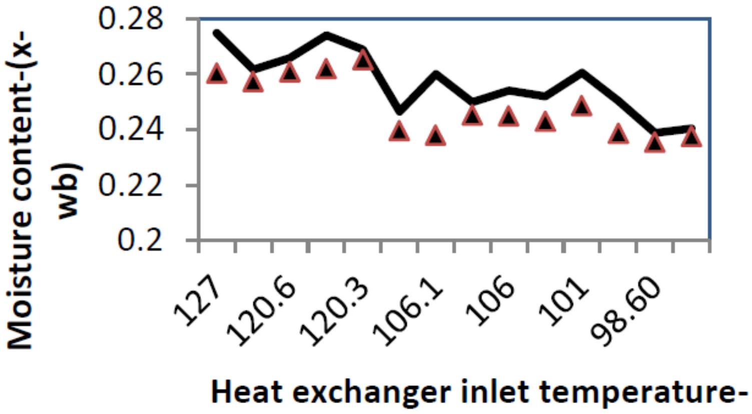

Fig. 9. Comparison between data (marker) and theory (solid line) using parameter k=1.25 in (1/h), and Me=6% db.

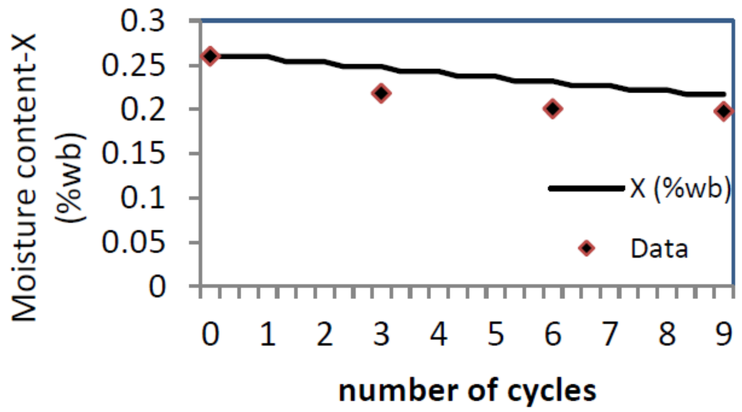

Fig. 10. Experimental results of the first stage experiments with 200 kg load and 26% wb. Initial moisture content as compared with theory (here k=1,25in (1/hr), Me=6% db).

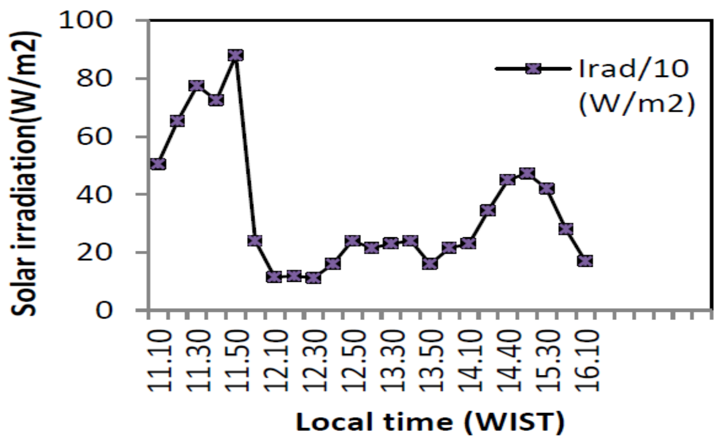

Fig. 11. Change in solar irradiation during the first 3 hrs of the drying experiment from 26% wb to 19.8%wb.

As shown in Figure 9, the observed data has indicated a faster drying rate as compared, to the calculated results using Equation 2. In addition, the larger value of parameter k, as compared to that obtained under the static thin layer drying condition was probably due to the turbulent manner of the drying process within the pneumatic conveyor. Bala [15], for example, from a thin layer drying test, has found a value of 0.426 (1/h) for rough rice, while wheat at 17.08 (1/h). In terms of Dv, Steffe and Singh (in Mujumdar [16]), obtained a value between 1 x10^{-11} to 6.9 x 10^{-11} m^2/s as compared to 1.8 x 10^{-11} m^2/s in this study showing that the value obtained was within the range published by Steffe and Singh [16].

6.3 Drying Performance of the Complete Solar Drying Set up

Figure 10 shows experimental results with 200 kg load and 26% wb initial moisture content. During this experiments the change in solar radiations, conveyor inlet and outlet air temperatures are shown, respectively, by Figures 11 and 12. These figures show that during the test the weather condition was mostly cloudy, and fluctuating, where 78.3% of incoming solar irradiation was below 500 W/m^2. By operating the auxiliary heating unit using a biomass stove, however, it was possible to maintain a relatively constant inlet and outlet temperature of the pneumatic conveyor between 40°C to 50°C. During the experiments the electric consumption of the recirculation blower was high at the first hours, but tends to a relatively constant value of 516 W as shown in Figure 13, where the mass flow rate of the recirculating grains was 602 kg/h. as estimated using Equation 10.

Figure 10 also shows the comparison between experimental data and the computational results using parameter k=1.25 kg/h (Dv, 5.07x10^{-5} m^2/h) and Me =6 % db. It shows that the drying time calculated using Equation 2 was longer than the observed value. This deviation might be due to the neglected influence of solar radiation during the drying process within the ICDC unit.

Using Equation 5, 6 and 8, the travel time of the grains across the pneumatic conveyor (t_{PC}), the solar collector-drying chamber (t_D), and including the tempering time within the hopper (t_T), was t_{PC}=0.0018 hrs., t_D = 0.0003 hrs and t_T=0.028 hrs., respectively.

Figure 14 shows the results of continuing test during the next day after the first test was terminated at 19.8%wb grain m.c. This test was also conducted under the condition of low solar irradiation (78.9% less than 500 W/m^2) as shown in Figure 15.

Figure 16, shows the drying air temperature at pneumatic conveyor inlet was between 51.1°C - 45.3°C while the consumed electric power shown in Figure 17.

The experimental time required to reduce the moisture content from the initial moisture of 19.8% (now with 192 kg attained within 7 hrs. This is comparable to the calculated drying time of 20 cycles or 20 cycles x 0.347 hrs./cycles=6.94 hrs.

Figure 18, shows the drying process using 380.5 kg (at initial m.c. of 27.1% wb). Based on the calculated trend, to reach 14% wb., the drying process would require 13 re-circulations or equivalent to 13 x 380.5 kg / 584.5 kg/h =8.48 hrs., which means that the drying process can be accomplished within one day.

Figure 19 shows the operating conditions during the test where the ICDC unit temperatures were fluctuating between 42°C-66°C. The pneumatic conveyor temperature, however, was maintained at relatively constant between 65-70°C at inlet and between 51°C -59°C at the outlet location.

Figures 19 and 20 show respectively, the variation in ICDC unit temperature with average value of 40°C with solar irradiation level always above 600 W/m^2.

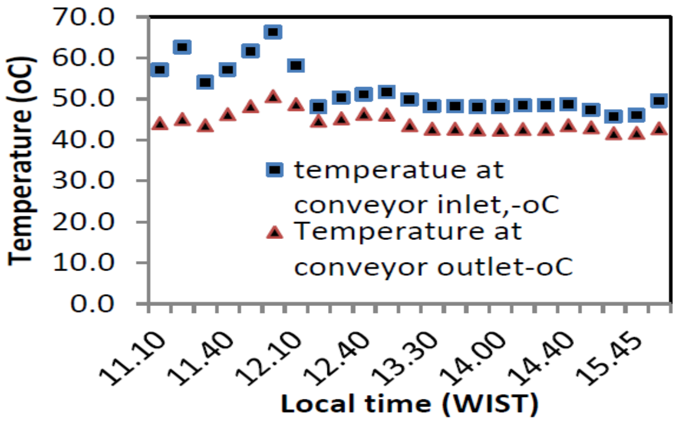

Fig. 12. Variation in conveyor inlet and outlet temperatures during the experiments.

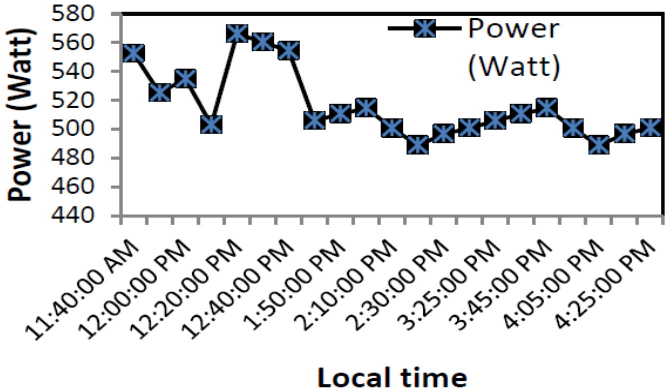

Fig. 13. Variation power consumed during the experiments.

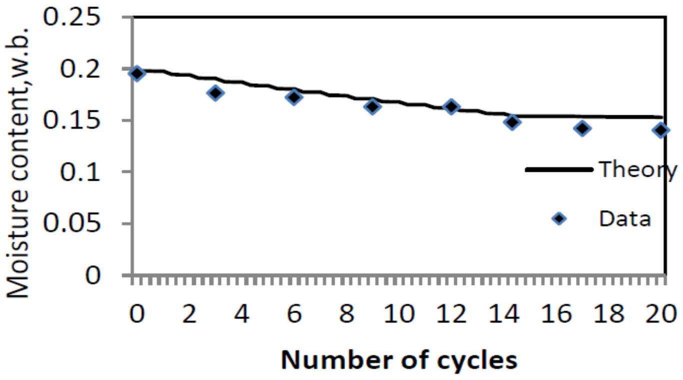

Fig. 14. Comparison between calculated results and data for drying test with 192 kg,19.8% wb initial moisture of rough rice, (k=1.25 in (1/h), Me=6% db.

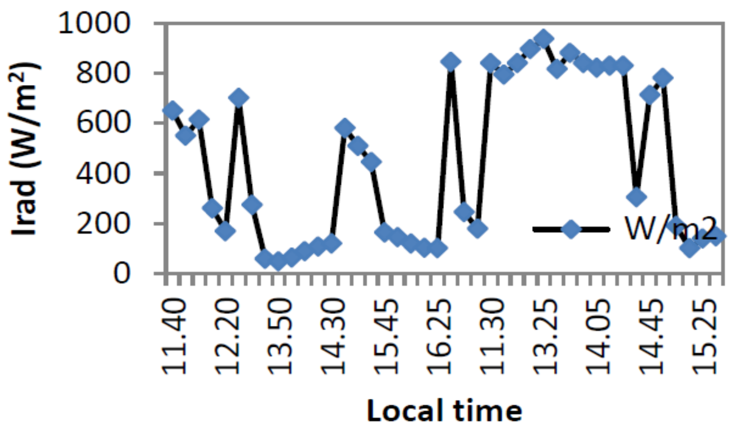

Fig. 15. Change in solar irradiations during drying test with 192 kg rough rice.

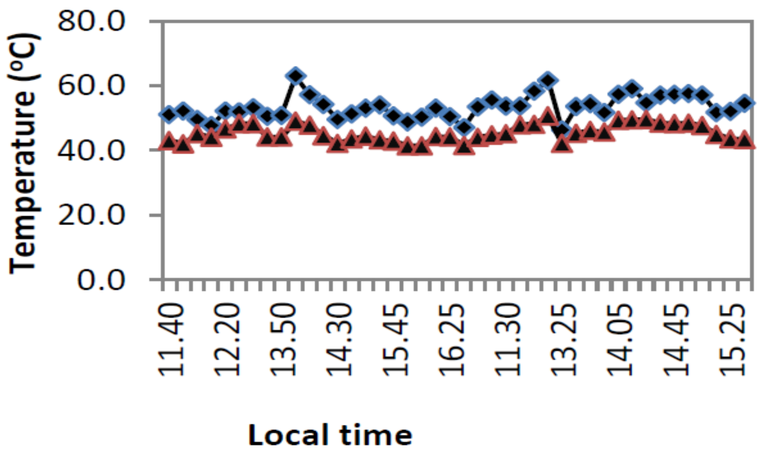

Fig. 16. Hot air temperature at pneumatic conveyor inlet (upper curve) and outlet (lower curve).

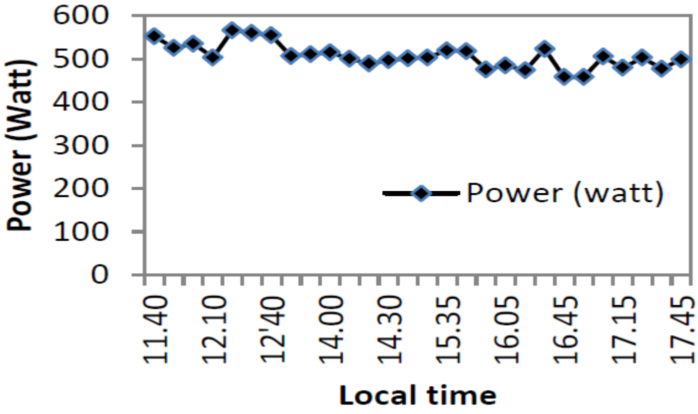

Fig. 17. Change in electric power consumed.

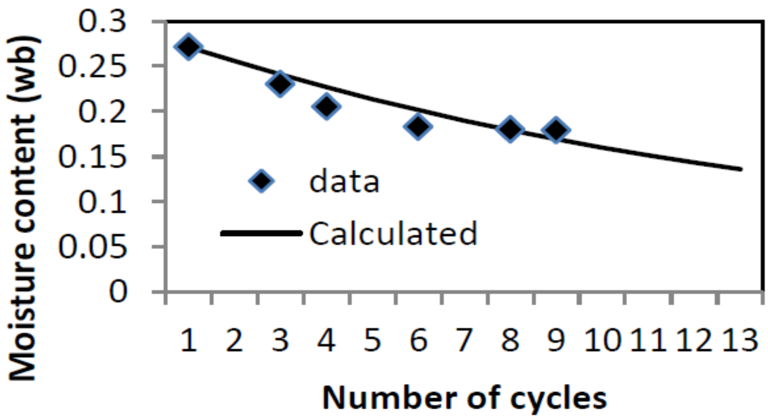

Fig. 18. Comparison between measured and calculated change in moisture content during drying test of 380.5 kg (27.1%wb).

6.4 The Specific Energy

Specific energy, S_E, is defined as the ratio of total input of commercial energy to the amount of water evaporated during the entire drying process. It can be expressed by:

$$S_E = \frac{P w\, t_D}{\{\frac{(X_i - X_f)W}{(1 - X_f)}\}} \qquad (14)$$

Here X_i, is the initial moisture content of the grains (% wb), X_f, the final moisture content and W, is the initial mass of rough rice before drying. The denominator of Equation 14 is in fact the total amount water evaporated during the drying process.

Using data of drying test with 200 kg load (26%wb) the specific energy, as defined above, was found to be 0,193 kWh/water evaporated or equivalent 0.695 MJ/kg water evaporated. In this case electricity was the only input from commercial energy used in the tested drying system which showed a very low value as compared to those using conventional mechanical drying.

6.5 The Drying Quality

Regarding the quality of the drying process using pneumatic conveyor, it was found that from 100 samples of dried grains only one occurrence each found from two groups of 10 grain samples. There was no occurrence of cracking detected in the remaining 80 grain samples. Therefore, it is recommended that pneumatic conveying system should be used as a proper means of conveyance method in a continuous solar drying system since beside causing less damage to the grain, it is also consumes less energy during the handling process of the grains.

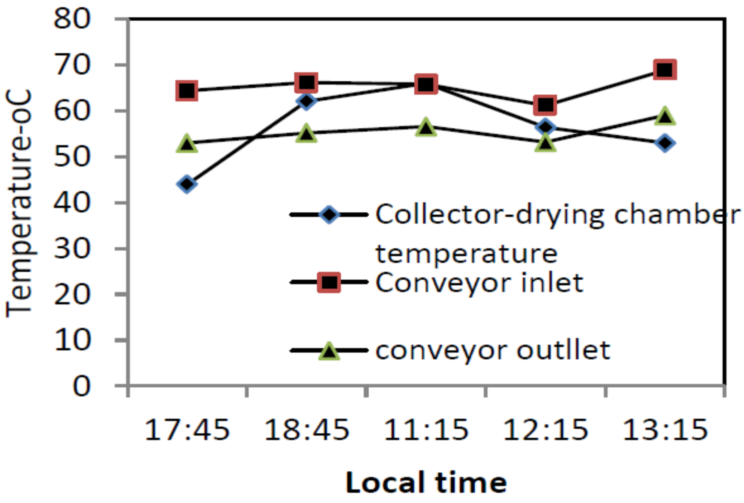

Fig. 19. Variation in air temperature within the ICDC unit during the experiment with 380.5 kg load of rough rice.

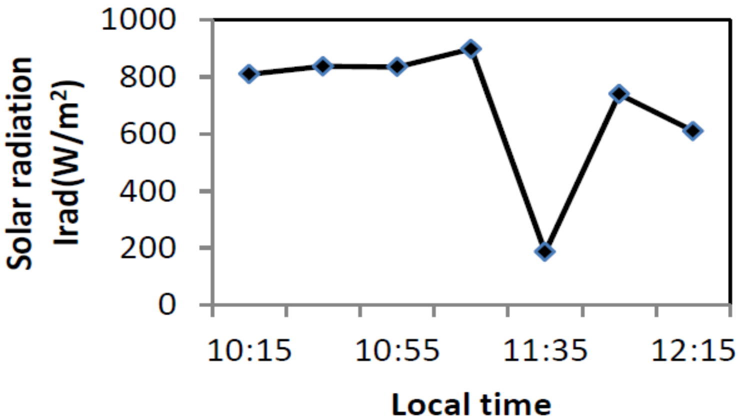

Fig. 20. Variation in solar radiation during the drying test with 380.5 kg of rough rice.

7. CONCLUSIONS

a. A 2.5 ton maximum capacity of a recirculation type hybrid ICDC solar dryer having 3 m in length, 3 m wide with a height of 3 m has been designed and constructed and later was tested under outdoor conditions. The time required to dry 200 kg of freshly harvested rough rice with an initial moisture content of 26% was 11 hrs and 22 minutes, while a test with 308.5 kg (27.1% wb) the required time was 8.48 hrs.

b. Experimental results have shown that power requirement to transport between 0.5 – 0.7 tons/hr. using a 4” pneumatic conveyor, inclined 60 degrees from the horizontal, to 3 m distance was between 500 – 600 W or equivalent to 0.87 W/kg/hr-0.89 W/kg/hr. for conveying rough rice to 5.44 m distance.

c. A modified form of Ergun type correlation equation for air flow across a fixed bed could be used to estimate the pressure drop occurring in the flowing two- phase, air and grain mixer.

d. Using the apparent mass diffusivity, Dv, of $5.07x10^{-5}$ m^2/h (or k=1.25 (1/h)), and the apparent equilibrium moisture content, Me=6 %db, with their respective travel time within each of the dryer component, namely within the pneumatic conveyor, the ICDC unit including the tempering time within the hopper, the experimental results were predicted with relatively good agreement using the diffusion theory, except for the process, however, on the average, had a higher value as compared to the experimental data probably due to the exclusion of the energy input from solar radiation in the model.

e. The total electric energy consumed during the drying process of 200 kg rough rice was 5.75 kWh, with specific electric energy value of 0.193 kWh/kg water evaporated or equivalent to 0.695 MJ/kg water evaporated.

f. The amount of cracks from the 200 kg load test was only 2 grains from 100 samples or equivalent to 2%.

g. Pneumatic conveying system should be used as a proper means of conveyance method in a continuous solar drying system since besides causing less damage to the grain, it also consumes less energy for recirculating the grains.

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NOMENCLATURE

A	area (m^2)
A	geometric coefficient in Equation 2
Ao	cross section area (m^2)
A_1,	cross section area of hopper (m)
Ap,	cross section area of pipe (m)
C_1	discharge coefficient (-)
C_f	Friction coefficient (-)
D_p	pipe diameter (m)
Dv	mass diffusivity (m^2/h)
g	acceleration due to gravity(m/s^2)
G_o	mass flux of air under superficial air velocity (kg/ m^2h)
H	pressure head (Pa)
H	absolute humidity (kg of moisture/kg of dry air)
H_h	height of hopper
ΔH_{fg}	latent heat of evaporation (kJ/kg°C)
k	the drying constant (1/hr)
Lp	pipe length (m)
L_{pc}	pneumatic conveyor pipe length (m)
L_d,	length of drying chamber-solar collector (m)
M	moisture content (%db)
Me	the equilibrium moisture content (%db)
N	rotation of the blower (RPM)
P	pressure (N/ m^2)
P_o	pressure at conveyor inlet (N/ m^2)
P_L	pressure at conveyor outlet (N/ m^2)
Pw	power (W)
Qa	volumetric flow rate of air (m^3/s)
r	radius of grains modeled as spherical body (m)
T_a	temperature of the air (^oC)
T_g	temperature of the grains (^oC)
t_T	tempering time (hrs.)
t_D,	travel time of grains within solar collector-drying chamber (hrs.)
t_{pc}	travel time of grains within pneumatic conveyor (hrs.)
V_o	superficial velocity of the air (m/s)
V_p	velocity of rough rice (m/h)
W	initial mass of the grains (kg)
Wa	mass flow rate of air (kg/s)
Wp	mass flow rate of rough rice (kg/s)
X_i	initial moisture content of the grains (% wb)
X_f	final moisture content of the grains (% wb)
y	distance travelled by grain from pneumatic conveyor inlet (m)

Greek letters

ε	void ratio (-)
γ	ratio between mass flow rate of air and that of rough rice (-)
μ	absolute viscosity of the air (kg/m s)
ρ	density of the air (kg/m^3)

Subscripts

a	air
D	collector-drying chamber
i	inlet
o	Outlet, initial
p	rough rice, pipe
pc	pneumatic conveyor
T	tempering

REFERENCES

[1] Kamaruddin A., 2007. Teknologi Berbasis Sumber Energi Terbarukan untuk Pertanian (Renewable energy Technologies for Agriculture), CREATA-IPB. ISBN978-979-96105-4-6.

[2] Imre L., 1995. *Solar Drying*. Chapter in *Handbook of Industrial Drying 2nd Edition*, AS Mujumdar, Ed., 373-451. Marcel Dekker, New York.

[3] Müller J. And W. Mühlbauer. 2011. *Solar Drying, in Modern Drying Technology: Energy Savings, Volume 4*. Editors: E. Tsotsas and A.S. Mujumdar, Wiley-VCH Verlag GmbH & Co. KGA, Weinheim, Germany.

[4] Sharma A., Chen C.R. and Lan N.V. 2009. Solar drying system: a review. *Renewable and Sustainable Energy* 13(6-7): 1185-1210.

[5] Lutz K. and W. Mühlbauer. 1986. Solar tunnel dryer with integrated collector. *Drying Technology, International Journal* 4(4): 583-603.

[6] Damardjati D.S., Trim D.S. and Haryono. 1991. Improving Rice Quality by Using a Solar-Supplemented Dryer for Paddy Drying. In *Proceedings of the 14th ASEAN Seminar on Grain Post Harvest Technology*, Manila, 5-8 November. Naewbanij J.O. and A.A. Manilay, Eds.

[7] Manalu L., 1999. Pengering surya dengan pengaduk mekanis untuk pengeringan kakao, thesis S2, (Solar drying with mechanical mixer for cocoa drying), Agricultural Engineering Science Division, the Graduate School, IPB, Indonesia.

[8] Kamaruddin A. and L.O. Nelwan. 2006. Installation of Solar Dryer with Rotating Drum in Kamare Village, Sulawesi, Report to the Directorate General of Electricity and Energy Utilization, CREATA, IPB.

[9] Kamaruddin A., Aep Saepul Uyun, Yefri Chan and Yendi Esye, (2010). Final report of the 1st year competence Grant of the Directorate General of Higher Education, Contract No.413/SP2H/PP/DP2M/VI/2010, June 11 2010.

[10] Nishiyama Y., 1973. Momi kansho ni kansuru kyuu moderu no Ooyooo (*English translation:*

Application of sphere model in rough rice drying). Doctoral Dissertation, the University of Tokyo

[11] Crank J., 1986. Chapter 6: Diffusion in sphere, in *The Mathematics of Diffusion*, pp. 89-91. Clarendon Press. Oxford.

[12] Bird R.B., Steward W.E. and Lightfoot E.N., 1960. Chapter 10: The equation of change for non-isothermal systems, in *Transport Phenomena*, pp 357-360. John Wiley & Sons, Inc. New York, USA.

[13] Henderson S.M and Perry. 1971. Chapter 11: Drying, in *Agricultural Process Engineering*, pp. 314-315. The AVI Publishing Company, Inc. Westport, Connecticut, 3rd Ed.

[14] Hanafi. 2006. Graduation thesis, Department of Agricultural Engineering, Fateta, IPB. Indonesia.

[15] Bala B.K., 1997. Chapter 6: Thin layer drying of cereal grains, in *Drying and Storage of Cereals*, pp. 118-125. Oxford and IBH, Publishing Co.PVT, LTD.

[16] Mujumdar A.S., 1995. *Handbook of Industrial Drying*, Volume 1, 2nd edition, pp113-159, Marcel Dekker, Inc. New York, Basel, Hongkong.

[17] Ahiduzzaman M and A.K.M. Sadrul Islam**.** 2009. Energy Utilization and Environmental Aspects of Rice Processing Industries in Bangladesh, Energies, ISSN 1996-1073. (www.mdpi.com/journal/energies).