Development of an Intermittent Solar Dryer for Cocoa Beans

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ABSTRACT

A solar dryer with thermal energy storage was developed for intermittent drying of cocoa beans. The prototype was built using readily available local materials. Drying mechanism was based on a combination of convective heating and direct radiation, with a provision for controlling the rate of airflow through the beans. The experimental model dehydrated cocoa beans from 53.4 to 3.6% moisture content (w.b) in a 72 hours inter-mittent drying process against ambient temperature and relative humidity in the range 25-30^{o} C and 58-98%, respectively. Quality assessment of the dried beans showed that beans of good quality attributes: pH of 6.35, acid value of 3.40 mg/g, with mildly bitter taste were obtained under free convective drying; whilst, increase in moisture re-absorption and acidic flavour were indicated with forced convective drying. The work, thus, provides a viable system for producing cocoa beans of good quality attributes, comparable with using the traditional sun-drying, but without the associated drudgery.

Keywords: Intermittent dryer, Solar dryer, Cocoa beans, Sun-drying, Dehydration, Nigeria.

1. INTRODUCTION

Cocoa beans must be dried to reduce its moisture content to a safe level for storage. The drying process is also a continuation of the oxidative stage of fermentation of the beans, thus, further reducing the constringency and bitterness of the product. Properly dried beans, usually at about 6-8% moisture content (wet basis) have reduce acidity and are characterized by the familiar ‘chocolate’ brown colour.

Methods of drying the beans are usually by sun-drying and artificial or, forced air drying, depending on some socio-economic considerations and prevailing climatic conditions. Sun-drying is simple and cheap: not requiring the expensive mechanical devices used in the artificial dryers, but it is also labour-intensive and there is much concern for a stable weather condition.

Fundamental works on the thin-layer drying characteristics of cocoa beans are limited and are not related to the bean quality (Bravo and McGraw, 1974; McDonald *et al*., 1981). Although, experimentation on slow drying using the ambient air had produced beans of acceptable quality, there was over-fermentation of the beans with inadequate heat and air movement (Thien and Yap, 1994). In the humid tropics, slow drying with ambient air is not sufficiently attractive because the prevailing environmental condition of about 29-32^{o} C and 80% relative humidity result in low drying potential.

A two-stage process reported by Duncan *et al*.(1989) in which the beans were first ventilated at ambient conditions to about 20% moisture content (w.b) followed by drying at 60^{o} C until 7.5% moisture content (w.b) gave quality attributes which were close to those of naturally sun-dried samples. Similar results were obtained from drying continuously at 40^{o} C; whilst, continuous drying at 60^{o} C resulted in poor quality beans. It is certain that a practical propriety system based on the two stage process will not be suitable for bulk drying because the drying zone in such system can not be uniform throughout the depth of the product. On the other hand, the rapid continuous drying occurring in the use of forced air, with air temperature of 60-70^{o} C causes the bean to have a strong acidic flavour, weak 'chocolate' flavour, and possession of other off-flavour (Wood, 1983; Duncan *et al*., 1989; Thien and Yap, 1994; Faborode *et al*., 1995).

It thus appears that the traditional sun-drying, though with some limitations, is the most appropriate method for producing cocoa beans with the best quality attributes. The beans are heaped up at sun-set, stored away from dews, and covered with thick tarpaulin over-night. It is, therefore, a rest period type of drying. It is necessary to keep the beans at higher temperature than the ambient, to eliminate the occurrence of moisture re-absorption. The intermittent process, occasioned by nightfall, aids the full realization of bio-chemical degradation, and browning reactions. Consequently, a solar dryer with thermal energy storage was contemplated. The storage will provide the thermal inertia, or capacitive effect to complement the solar collector during periods of bad weather and at sunset; and also, provide the needed impedance against moisture re-absorption during the rest period.

Solar thermal technologies have been used in various applications either, as natural convective type dryers, or with forced ventilation, in the drying of coffee, paddy, cassava, bananas, mango, medicinal plant and herbs (Sampaio *et al*., 2007; Lutz *et al*., 1987; Müller *et al*., 1989; Madhlopa and Ngwalo, 2007; Bhandari and Gaese, 2008). Materials which have been used as absorbers and thermal energy storage include granite, rock bed, pebble bed, sand, water, and thermic oil (Khattab and Bdawy, 1996; Helwa and Abdel Rehim, 1997; El Sebaii *et al*., 2002). The choice of material is guided primarily by the product of the material density and its specific heat. The higher the product, the better the material, provided the operating temperature can be sustained.

The focus of this work was to exploit the combined benefits in the traditional sun-drying practices and the continuous drying at low temperature, at about 40-60° C, in the drying of fermented cocoa beans. The effects of air flow rate during active solar drying and the available stored thermal energy during the rest periods on the drying characteristics, and on the quality of the cocoa beans were also investigated.

2. DESIGN AND CONSTRUCTION

2.1 Philosophy of Design

The dryer was conceived as low-cost, easy-to-fabricate and easy-to-operate equipment, using available local materials, in order to make it suitable for most peasant farmers, with little or no formal education.

2.2 The Experimental Dryer

The experimental dryer (Figs.1a & b) was made mainly of wood and consisted of the following major components: the solar collector; the drying chamber and the heat storage chamber. An air duct connects the upper end of the solar collector to one end of the drying chamber; while, the other three sides were partitioned internally, 125 mm wide, to form the heat storage chambers. The surfaces of the collector, the drying chamber and heat storage chambers were covered separately with glass doors. The contacts were firmly closed to minimise infiltration losses. A five-speed axial flow fan is located inside the air duct to blow hot air during the period of insolation: drawing hot air from the solar collector and discharging onto the beans in the drying chamber. Consequently, the beans are dried by a combination of convective heating of the hot air and the direct radiation through the glass cover. The dryer was mounted on a wheeled frame, made from $50 \times 50 \times 3$ mm angle iron. The prototype was designed to hold a batch of 50 kg of wet cocoa beans. The design features of the major parts are briefly described below.

2.2.1 The Solar Collector

The solar collector is basically a top-open, wooden box, 1100 x 1000 x 200 mm made from 10 mm thick plywood. The box was inclined to keep its top surface, covered with 3.18 mm thick glass, at about 15 degrees to the horizontal. The solar energy received by a flat collector is at maximum (Gbaha *et al.*, 2007) if the inclination angle of the collector to the horizontal is such as $(\varphi - 10^o) \le \beta \le (\varphi + 10^o)$; where β is the angle of inclination and φ is the latitude of the location. The latitude of Ile-Ife is 7° 48$^{/}$ N.

The performance evaluation of the collector, which is significant for its dimensioning, was based on the Hottel-Whiller equation (Duffie and Beckman, 1974) on the assumption that it is applicable to this design. In the steady state, the thermal efficiency η is defined by

$$\eta = \frac{mc_p (T_d - T_a)}{A_c I_T} \quad \ldots \quad \ldots \quad \ldots (1)$$

where, m is the mass of product in kg; c_p, specific heat of product in kJ kg^{-1} K^{-1}; T_d, dryer temperature in ^{o}C; T_a, ambient temperature in ^{o}C; A_c, collector surface area in m^2; and I_T, total incident radiation in kW/m^2.

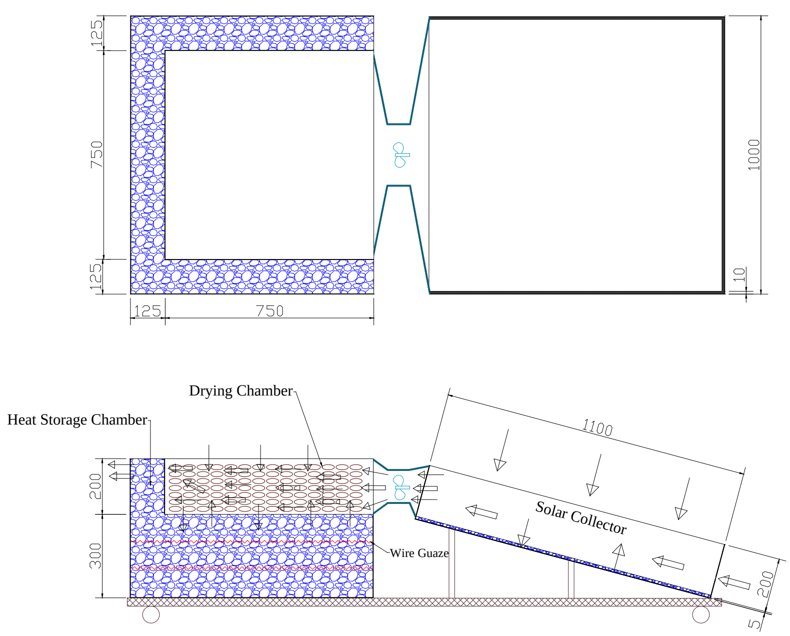

Figure 1a. A schematic illustration showing plan view and elevation of the experimental solar dryer: ⇨, air flow; →, heat flow

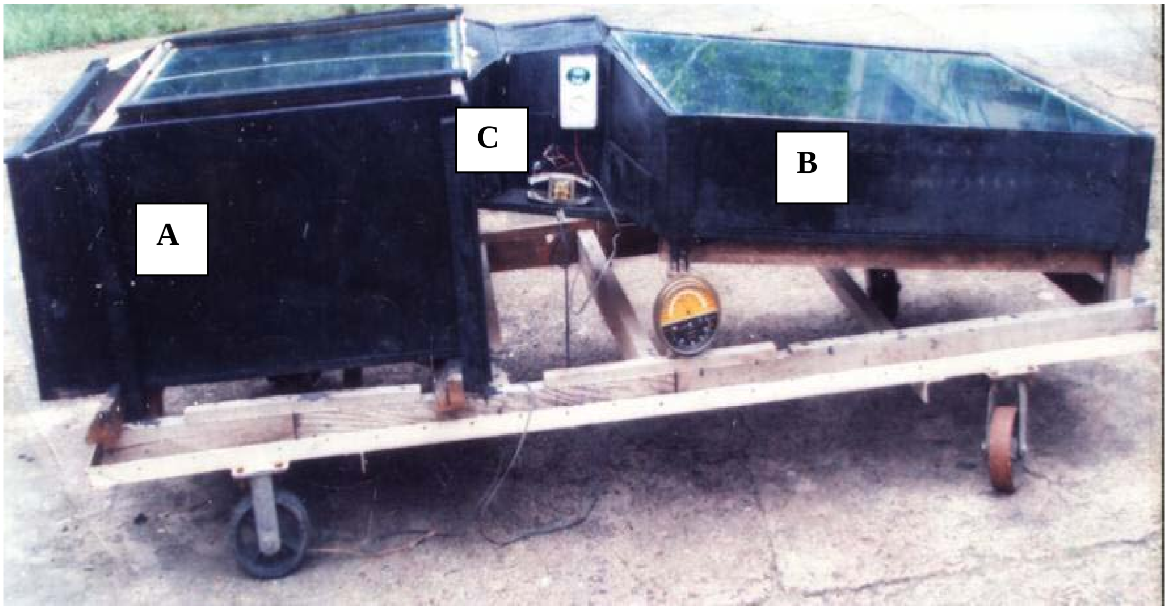

Figure 1b. Picture of the experimental solar dryer: A, drying chamber; B, solar collector; C, fan housing

The temperature of the hot air at the discharge port was assumed to be 60° C, being the upper limit of the temperature proposed for the design. The ambient temperature, T_a during the period of insolation was taken to be 30° C, being the mean of the prevailing ambient temperature reported in the literature (FAO, 1994). The total incident radiation flux, $I_{T,}$ on a tilted surface as given by Sukhatme (1981) was employed.

$$I_T = I_b R_b + I_d R_d + (I_b + I_d)R_r \qquad \ldots \qquad \ldots \qquad \ldots (2)$$

where, I_b is the hourly beam radiation; I_d, hourly diffuse radiation; R_b, tilted factor for beam radiation; R_d, tilted factor for diffuse radiation; and R_r, tilted factor for reflected radiation.

The collector was loaded with a 5 mm layer of black painted gravel to increase the heat absorption rate. A sheet metal cover, 1.3 mm thick, separated the gravels from the air plenum. The air space was provided with inlet and discharge ports at the lower and upper ends, respectively. Therefore, the hot air was transported by its buoyancy and the suction of the fan. A flap was provided for closing the discharge port when necessary.

2.2.2 The Drying Chamber

The drying chamber is also a wooden box $750 \times 750 \times 200$ mm, and was dimensioned based on the bulk density of cocoa beans (Faborode and Omotade, 1995). Thermal energy balance was computed considering the useful energy required for drying, and the thermal losses of the system. The heat required E to evaporate the moisture and also keep the beans at the dryer temperature was computed from Eqn (3), based on basic principles of heat transfer (Karlekar and Desmond, 1982).

$$E = m_c c_c dT + m_w L \qquad \ldots \qquad \ldots \qquad \ldots (3)$$

where, m_c is mass of cocoa beans in kg; c_c, specific heat of beans in kJ kg^{-1} K^{-1}; m_w, mass of moisture removed in kg; L, latent heat of water vapourisation in kJ/kg (2256 kJ/kg, from Liley, 1997); and dT, change in temperature in ^{o}C.

The collector was designed to dry the beans within 3 days for an average of 8-hour period of insolation and rest periods at nights. The bed of gravels was overlaid with a perforated plate (5 mm diameter holes, 10 mm apart) to retain the beans and to facilitate convective heat flow from the gravels onto the beans during the rest periods. The layers of gravels were separated by wire gauze, to enhance experimental investigations. Similar holes were drilled into the plywood partitions separating the drying and heat storage chambers, to facilitate heat flow between the two chambers. The holes are appropriate because the least principal dimension of properly dried cocoa bean is about 6 mm (Faborode and Omotade, 1995). The door of the glazed top surface was latched onto the box; against a soft rubber seal in-between the contacting edges, to minimise infiltration losses.

2.2.3 Heat Storage Chambers

The heat storage chambers provided for passive heating of the beans, particularly, during the rest periods. Preliminary investigations indicated a minimum of 21° C ambient temperatures T_a hence, equilibrium temperature T_e of 23° C for a rest period of 12 hours was assumed. The temperature of the beans at onset of rest period T_b was taken as 40° C (the lower limit proposed in the objective). The chambers were completely filled with gravels to absorb heat during the day and release it to the crop at night. The lower sections of the heat storage chamber are continuous with the bed of gravels in the drying chamber. The quantity of gravels which was required in the chambers, to keep the temperature inside the dryer above the ambient throughout the night was determined (Karlekar and Desmond, 1982) by

$$\frac{T_e - T_a}{T_b - T_a} = e^{(-hA/\rho c v)t} \quad \ldots \quad \ldots \quad \ldots (4)$$

where**,** relative to the drying air, h is the convective heat transfer in kW m^{-2} K^{-1}; ρ, density in kg/m^3; c, specific heat in kJ kg^{-1} K^{-1}; v, volume in m^3; t, duration of rest period in s; and A, surface area of drying plate in m^2.

Thermal losses of the system, resulting from conductive, convective and radiative exchanges from the beans and gravels in the dryer and the environment were considered.

2.3 Test Procedure

2.3.1 Dryer Performance

Freshly fermented cocoa beans were obtained from the University Research Farm, Obafemi Awolowo University, Ile-Ife, Nigeria, at the start of each experiment. The moisture content of the samples were determined, drying the beans at 103° C in a ventilated oven until constant weight was achieved following AOAC (1984). The samples were measured using a Mettler PL 1200 digital display electronic balance with precision of 0.001 g.

The dryer was tested during the raining season in Western Nigeria. During this period, the ambient air has the least potential for drying; therefore, the performance of the dryer is expected to be better during the dry season. Temperatures in the dryer were measured using a digital thermocouple (K-type, XMTA-7000 TAIFA®) arranged at the center and at the surface of the product. The relative humidity of the ambient air was measured near the dryer, using a psychrometer. The temperature of the ambient air was measured with mercury-in-glass thermometers. Air from a 10 W axial-flow electric fan was calibrated using a hot-wire anemometer. The mean of three readings was reported for each observation. The dry-bulb temperature inside the dryer was compared with the ambient, for both the day and the night periods with or without gravels in the heat storage compartment, and with varying depths of bed of gravels in the drying chamber.

The dryer, loaded to a depth of 160 mm, was further tested on its thermal effectiveness in drying cocoa beans under natural and forced convections. The samples, loaded into the dryer were weighed on a top pan balance with a precision of $0.1\,g$. The drying was conducted for 72 hours with rest periods at nights, from 6 pm to 6 am. Traditionally, cocoa beans are dried for 5-6 days and the product is often infested with mould and slate. The moisture content of the beans was measured every six hours during the drying process. The traditional sun drying of some sample was also employed simultaneously, to provide for comparisons. Also, where possible, the experimental samples were evaluated against the International Standard for dried cocoa beans.

2.3.2 Quality Assessment of Dried Beans

The dried beans were examined for colour, taste, and occurrence of slate or mould. Quality assessment was based on the pH, oil content, acid value and Free Fatty Acid level of the dried beans. The pH and acidity were determined according to Duncan *et al.* (1989). Ten grammes of the nibs were homogenized in 200 mL distilled water; the homogenate was filtered and the pH of the supernatant was measured using a digital pH meter (CD 70, MPA). A 25 mL aliquot was titrated to pH of 8.0 with sodium hydroxide (0.01M) to determine the acidity of the beans. The Free Fatty Acid content was determined according to AOAC (1984). One gramme of grounded cocoa nib was poured into a conical flask (250 mL); 50 mL of 0.5 M ethanonic potassium hydroxide were added to each of the samples. Heat was applied to dissolve the solution and allowed to cool. One to two drops of phenolphthalein indicator was added and the solution was titrated with 0.5 M HCl until the colour changed. The percentage FFA was then determined as the percentage molar equivalent of the NaOH titre to the mass of cocoa nib sample.

The effect of airflow rate on the quality of the dried cocoa beans was evaluated in terms of the pH, acid value and taste of those dried under free convection compared with those dried under forced convection at various airflow rates.

3. RESULTS AND DISCUSSION

3.1 Temperature Fluxes

The moisture content of the cocoa beans at the time of the experiment was found to be 53.4% (w.b). Although, the beans were apparently wet there was no free surface water on the bean.

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Temperature variation in the dryer for a 24-hour period, starting from 6 am on the first day of the three day drying period (13th May) is shown in *Fig*. 2. The temperature in the dryer ranged from a minimum of 31° C at 6 am to a maximum of 54° C at 3 pm. The corresponding range of ambient temperature was 25 to 30° C. The prevailing ambient relative humidity was a minimum of 58% during the daytime whilst, it was relatively stable at 98% during the night (rest period). Although, the temperature gain was marginal (between 6 and 24° C) it was consistently a positive gain, showing that adequate thermal resistance against the colder environment was maintained.

Furthermore, as shown in the *Fig*. 2, the inside temperature of the dryer evolved in the same direction as the ambient temperature. Because, ambient temperature is related to the incident solar radiation (Boes, 1981; Gbaha *et al*., 2007), the drying air temperature can be estimated from available meteorological data to replicate the design elsewhere. The results further show that the heat required for keeping cocoa beans at a higher temperature than the ambient, during rest periods, to prevent moisture re-absorption, can be adequately conserved in suitably glazed gravels. This will eliminate the drudgery involved in the traditional sun-drying (heaping the beans and covering with tarpaulin at sunset). At such times the fan should be switched off to prevent rapid loss of conserved heat.

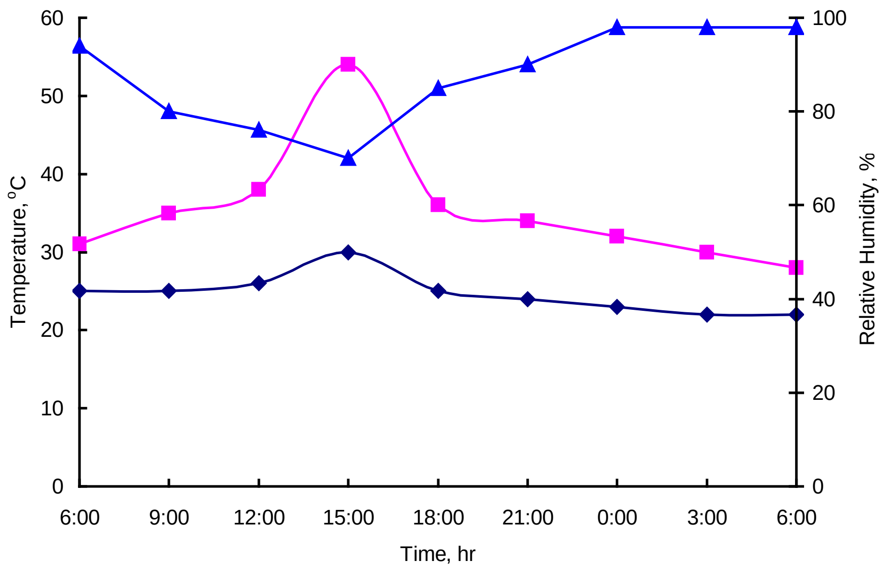

Figure 2**.** Day time temperature variation in the dryer: ♦, ambient; ■, dryer; ▲, relative humidity

3.2 Effect of Gravels in the Storage and Drying Chambers

The variation of the inside dryer temperatures at rest period with thickness (0, 65 and 130 mm) and depth (60, 160 and 300 mm) of gravels in the heat storage and drying chambers, respectively, are shown in *Figs* 3 and 4. Temperature inside the dryer was fairly constant and consistently above the ambient, but the effects of increasing the thickness and depth of gravel were not significant ($p \geq 0.05$). This implies that a minimum quantity of gravels, depending on the size of the dryer, is required in maintaining dryer inside temperature above the ambient temperature. This observation requires further investigations for insight into heat migration within cocoa bean, to establish the minimum value from fundamental principles.

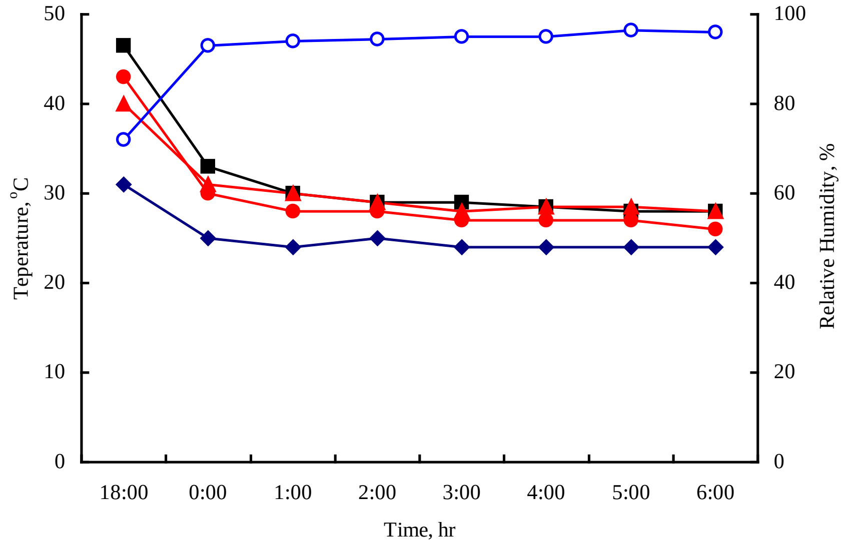

Figure 3. Rest period temperature variation with depth of gravel in drying chamber: ■, 60 mm deep; ▲, 160 mm deep;●, 300 mm deep; ♦, Ambient; ○, relative humidity

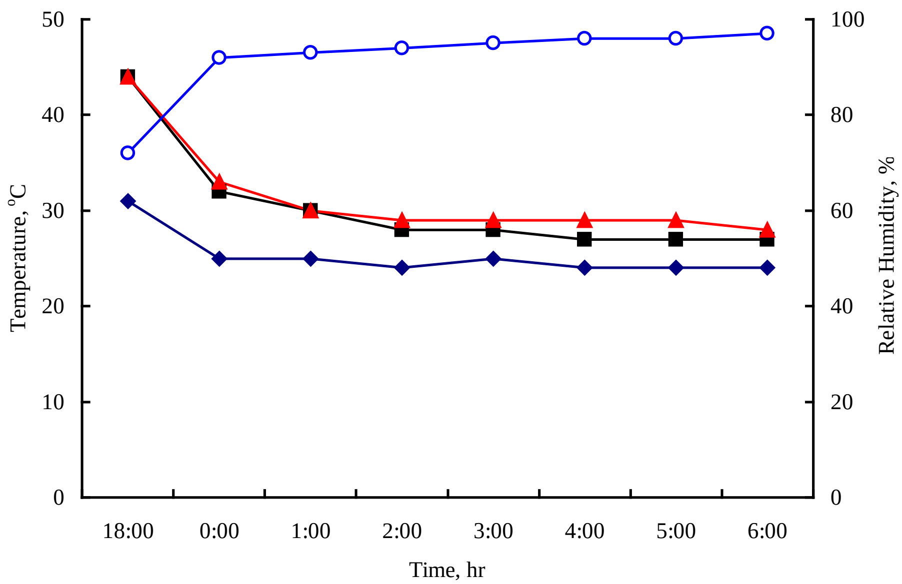

Figure 4. Rest period temperature variation with thickness of gravel in drying chamber: ■, 65 mm thick; ▲, 130 mm thick; ♦, ambient; ○, relative humidity

3.3 Drying Kinetics

The curves presented in *Fig*. 5 show the reduction in moisture content of the cocoa beans under free and forced convection at the corresponding drying time in the dryer. The drying rate in time *Fig*. 6, which was derived from *Fig*. 5, by calculating directly the derivative dM/dt from the experimental plots shows three distinct drying phases. It consists of a short initial, constant rate. This is an isenthalpic .phase, since the energy received by the product is entirely used in the vapourisation of surface water. The second phase consists of two stages: rapid deceleration in the drying rate and a slower deceleration. This reveals the difficulty with which the interstitial water migrates to the surface as the product becomes dryer. The drying process terminates when the moisture content balance of the product with the drying air is obtained.

At the initial, high moisture content (53.4% w.b) the interstitial water readily migrates to the surface by capillary forces. The water is redistributed into the capillary tubes by moisture diffusion in the bean, probably from its centre with higher moisture level to its drier outer surface. Once the water reaches the product surface, it is evaporated by the diffusion phenomenon. The drying is, therefore, enhanced by an increase in the temperature gain of the drying air. At the lower moisture content of the product, there is higher resistance to the migration of the water to the surface hence, the drying rate is slower.

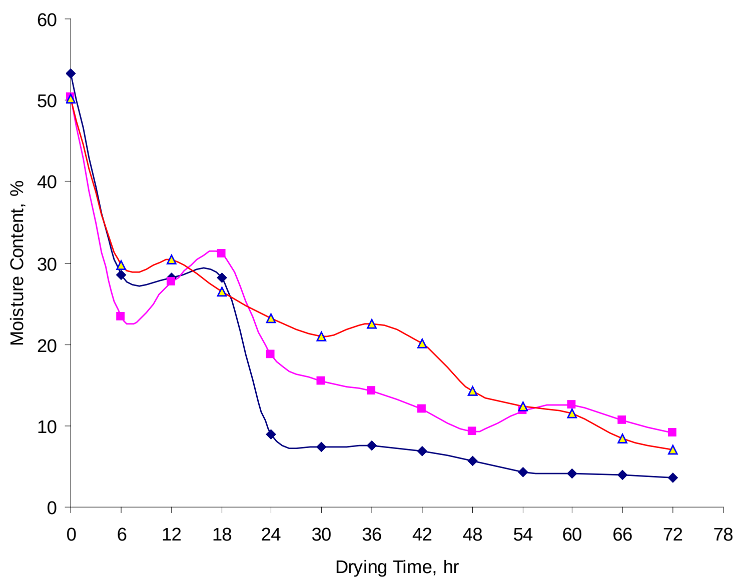

Figure 5. Moisture content of cocoa beans under free and forced convective drying in the dryer: ♦, free convection; ■, air flow at 1.02 m^3/min; Δ, air flow at 1.32 m^3/min

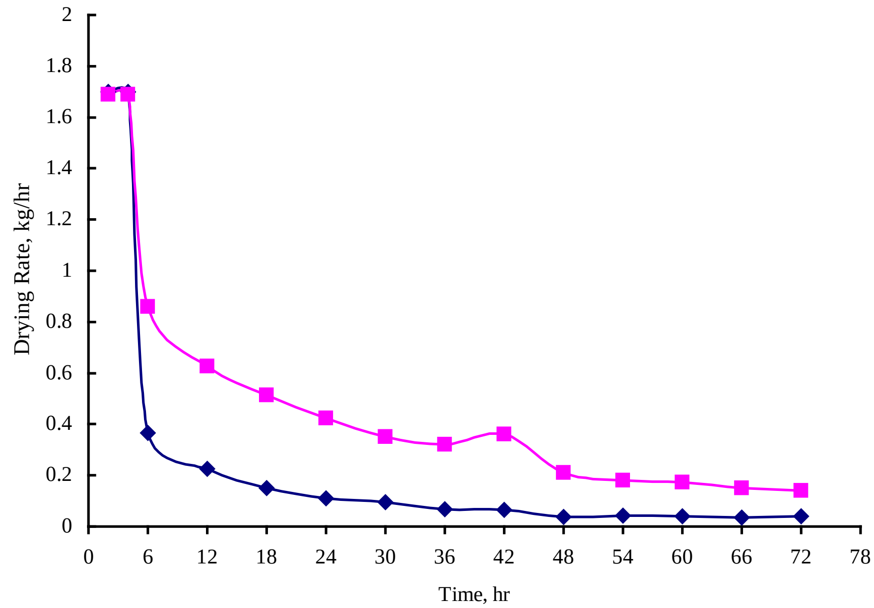

Figure 6. Drying rate of cocoa beans using the solar dryer and sun drying method during the period of drying: ♦, dryer; ■, sun drying

Similar curves are reported in the literature in the drying of cassava, coffee, medicinal herbs and grains (Müller *et al*., 1989; Sampaio *et al*., 2007; Faborode *et al*., 1995 and Gbaha *et al*., 2007). It is also interesting to note in *Fig*. 5 that the product from the free convective drying attained equilibrium moisture content of 3.56% (w.b); whilst, 9.09% and 7.11% (w.b) were obtained with the forced convective drying, with 1.02 and 1.32 m^3/min airflow rates, respectively. Furthermore, the curves shows regular occurrence of moisture re-absorption, between 1.00 and 3.00 a.m., throughout the three day drying period. The re-absorption is more pronounced with the forced convective drying. The moisture re-absorption may be attributed to the high relative humidity (98%) of the ambient air at this time and the hygroscopic nature of cocoa beans; the moisture-laden air is sucked by the fan into the drying chamber, thus, rewetting the beans at a higher rate. The period corresponding to the 24 to about 42 hour on *Fig.* 5 was particularly wet and cold because it rained, so that moisture re-absorption increased with the rate of air flow. Using the air with high humidity in drying is clearly against theory, which confirms that forced convection is not beneficial during the cold rest period when a solar dryer is employed. In practice, the fan should be turned off and the air vent closed, to eliminate the influx of the humid air. It therefore, suggest that the practice of observing an holding period, reported by Sampio *et al*. (2007) in the drying of coffee in forced convective dryers, is applicable to solar drying of cocoa beans.

3.4 Physical and Chemical Analyses of Dried Cocoa Beans

The physico-chemical characteristics of the beans, using the dryer are shown in Table1. In all the tested attributes, the solar dried samples compared favourably with the sun-dried samples. The qualities of both the solar dried and sun-dried sample are within the acceptable level in International Standards with respect to acidity, pH, and taste flavour. All the samples under free or forced convection in the dryer were properly dried showing dark reddish beans; whilst, in one occasion, the sun-dried sample was poorly dried. Such in-efficiencies are common in practice with sun-dried cocoa beans, particularly during the wet seasons; and in some cases with direct solar dryers (Hii *et al*., 2006).

Test results show that the beans under free convection are of superior qualities with pH of 6.35, acid value of 3.40 mg/g and mildly bitter taste; against the corresponding attributes of 5.18, 3.24 mg/g and mildly bitter taste for low air-flow rate; and 4.79, 3.20 mg/g and bitter taste for high air-flow rate. Cocoa beans under forced convective drying are therefore more acidic, with the acidity increasing with increasing heating air speed. This may be due to a sealing of the beans testa under the vortex of flowing air, thus, preventing the diffusion of the acetic acid from the beans. Consequently, a balance of the diffusion of moisture and its removal by the flowing air will present an optimum condition. Future research should investigate this optimal air speed against the required pressure resistance in deep bed drying.

There was no difference in the flavour of the sun-dried and the solar dried sample at the two air speeds. Such observations had been reported by Thien and Yap (1994) in the comparison of the qualities of sun-dried and air blown cocoa beans.

4. CONCLUSIONS

It can be concluded from this work that intermittent solar dryer is appropriate for drying cocoa beans to safe moisture level (3.6%, w.b) within 72 hours. The essential quality attributes of the beans are comparable with the product from the traditional sun drying.
Heat required in preventing moisture re-absorption in the beans, during the rest period, can be adequately conserved in suitably glazed gravels; whilst, forced convective drying increases acidic flavour in the beans and accentuates moisture re-absorption under humid ambient air.

Table 1. Qualities of dried cocoa beans under free and forced convection in the dryer compared with sun-drying

Attribute	Air flow, m^3/min			
	Free convection	1.02	1.32	Control+
Oil Content, %	31.7 (38.5)*	41.6 (29.5)	31.2 (32.4)	
pH	6.35 (6.46)	5.18 (5.35)	4.97 (5.20)	6.80
Acid Value, mg/g	3.40 (3.32)	3.24 (3.32)	3.20 (3.24)	3.50
Free Fatty Acid, mg/g	0.42 (0.42)	0.41 (0.42)	0.40 (0.41)	0.50
Taste	Mildly Bitter (Mildly Bitter)	Mildly Bitter (Mildly Bitter)	Bitter (Mildly Bitter)	
Colour	Dark reddish brown (Dark reddish brown)	Dark reddish brown (Dark red)	Dark reddish brown (Dark reddish brown)	
Slate	None (None)	None (None)	None (None)	
Mould	None (None)	None (None)	None (None)	

* Numbers in parentheses are the quality attributes of samples using the traditional sun-drying method
+ International Recommendation

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