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LIFE CYCLE COST ANALYSIS OF A MULTI-TRAY SOLAR DRYER WITH THERMAL ENERGY STORAGE BED

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ABSTRACT

A simple multi-tray natural convection solar dryer incorporating a sensible thermal energy storage bed has been developed using locally sourced materials. The sensible heat material is gravels of 45kg beneath the solar air heater. Test evaluation shows a temperature range of 29 to 56.5°C for the drying chamber while the heat storage bed temperature ranges between 31 to 57.8ºC at the uppermost part of the bed. It took 48 hours to reduce the moisture content of 7.50kg of fresh tomatoes at 93% to 5.5% under the weather condition of Bauchi in the month of February. Samples dried with the solar dryer were of superior quality compared to the open sun method. The computed payback period of the solar system ranges from 2.42 to 4.28 years using the annualized cost method and is lower than the expected life of the dryer. Also the amount of money that could be save from using the system compare to an electric powered dryer is worked out including the present worth, annual cash flow and cost of drying.

Keywords: Indirect solar dryer, thermal energy storage material, life cycle cost, payback period.

INTRODUCTION

Reduction of post harvest losses significantly contribute to the availability of food. A significant percentage of these losses are related to improper and/or untimely drying of foodstuffs such as cereals, grains, pulses, tubers, meat, fish, vegetables, etc. Drying is a simple process of moisture removal from an agricultural product in order to attain the desired moisture content and can be achieved through several methods such as open-sun drying, solar drying and mechanized drying. Solar drying is an energy intensive operation and depends on climatic conditions (humidity, wind speed, solar radiation, cloud cover, etc.) and drying materials' properties (chemical composition, physical structure, size, shape, etc.) (Garg and Prakash, 2000). The removal of moisture prevents the growth and reproduction of microorganisms that causes decay, reduces the product weight and volume as well as the transportation cost. The drying of agricultural produce under the sun is a common practice most especially in developing countries. Traditional method of drying involves spreading the crops on concrete floor, mats, tarred surface roads and other forms of material and turned regularly until they are sufficiently dried to the desire moisture content. This method is characterized by a number of shortcomings including; lack of process control, non-uniformity in the dried product, soaking by rain, theft and vandalism, contamination by dust, rodents, and other domestic animals (Ezekoye and Enebe, 2006; Ogunkoya *et al.*, 2011).

Also, prolong open sun drying often causes deterioration of vital ingredients like vitamins, minerals and sensory characters of the dried product and thus, less market value (quality falls below local and international market standards). However, this method is more affordable to the farmers. Solar drying method converts sun's radiation into heat for drying of agricultural produce at a superior drying rate compared to the open sun drying method with improved quality of dried products at a relatively low cost. The solar collector supplies the product with hot airflow either generated naturally due to density changes resulting from temperature differences or through forced convection by incorporating a fan or blower in the drying system. Solar dryers can be constructed from locally available materials and are useful in areas where fuel or electricity is expensive, land for sun drying is insufficient or expensive, sunshine is plentiful but the air humidity is high (Fellows, 1997). Besides, solar drying offers reduction to environmental risk compared to the mechanized drying method. Different types of solar dryers with varying sizes and designs have been developed and tested with some degree of efficiency. Studies have shown that solar dryers with auxiliary heating sources such as biomass back-up or thermal energy storage (sensible heat storage or latent heat storage) have better drying performances in terms of speed and quality of dried product. The inclusion of the heat storage unit elongates the service periods of solar dryer systems to overcome low solar radiation periods and even work at night hours (Gutti *et al.*, 2012; Shalaby, 2012). This research work investigates the sensible heat energy storage performance of gravels in an indirect multi-tray solar dryer for tomatoes drying.

Design Consideration

The solar crop dryer is designed for drying of agricultural produce that require low temperature drying in order to preserve the nutritive value of the crops after drying most especially vegetables and fruits. Vegetables and fruits were chosen for the design because of their importance in the human diet and tomatoes were selected as the produce study. Generally, vegetables are seasonal and highly perishable due to high their percentage of moisture in them especially at harvest period (Latapi and Barrett, 2006; Nwokoye and Okeke 2008; Ehiem *et al.*, 2009). Solar drying of vegetables makes available the dried product which cannot be consume completely at the time of harvest allowing consumers to buy the products on a year round basis. Besides the availability of the products all year round, it prevents wastages, preserved nutritive quality as well as viability of seeds (Brooker and Fred, 1974; Birewar, 1996; Mu'azu, 2012). The design looks into the intermittent nature of solar radiation and therefore incorporates a heat storage system which is capable of storing and releasing heat to the drying chamber during off-sunshine hours using gravel material.

Figure 1: Side view of the indirect solar dryer

Solar Energy Collector/Heat Storage System

The solar collector consists of a vee corrugated aluminium sheet as an absorber plate with dimensions of 1.4m x 0.6m x 0.3m (Length × Breadth × Height) and a single glass cover with 0.004m thickness. The vee corrugated aluminium sheet was painted black on both sides for better heat absorbing capacity. Underneath the solar collector system is the heat storage unit which houses the gravels for the heat storage. During a sunny day, as the air passes through the air inlet of the solar collector unit, the air gets heated by the absorber plate and flows into the drying chamber. The absorber plate also conducts part of the heat to the heat storage material underneath it. The frame of the solar collector/heat storage system was constructed with plywood and properly lagged with saw duct of 50mm thickness to minimize heat losses to the surroundings.

The drying chamber and conical chimney

The drying chamber frame was constructed from a melina wood (soft wood) with dimensions of 1.350m x 0.6m x 0.5m (Length × Breadth × Height). The drying chamber houses three trays of aluminium wire mesh which holds the produce to be dried, a door for loading and unloading. The trays were placed at a vertical distance of 0.2m apart. The effective dimension of each tray is 0.55m x 0.55m (Length × Breadth). A wire mesh is also riveted to the base of all the frames of the trays. Each drying tray could conveniently hold 2.5kg of fresh tomatoes chips at a time. All the trays can be easily reached by an average man of height 1.62m. The bottom of the drying chamber was covered with a base board made of plywood painted black. The use of plywood for the walls of the drying chamber minimise the rate absorption by external walls of the drying chamber while the top and bottom were all covered foam for insulation to reduce heat losses in order to maintain a uniform drying chamber temperature. The dryer system has a conical chimney made of mild steel and of 300mm height and 100mm diameter for easy of airflow to the top. The chimney also contain exhaust hood to prevent rain or water from entering the drying chamber from the top.

Techno-Economic Analysis

Cost Economics of Solar Cabinet Dryer for Drying of Tomatoes Slices

The economic feasibility of the solar cabinet dryer for the drying of tomatoes slices was calculated by considering the initial investment of dryer, average replacement cost of aluminium wire mesh, cost of raw material and selling price of the material after drying. The cost break up for the solar cabinet dryer as computed is Forty-Five Thousand, Nine Hundred Naira (#45,900).

Annual Thermal Outputs (Life Cycle Savings)

The energy output per year from the solar natural multi-tray dryer with a heat storage unit is the thermal output from the dryer. The dryer was used to dry 7.5kg of tomatoes (2.5kg/tray). The drying time was 48 hours of clear sunny days of 8 hours (9.00am to 4.00pm) and the store heat which was used to extend the drying for 2 and half hours by using the solar dryer. 6.9444kg of moisture as M_R was removed in same period of drying from drying 7.5kg of tomatoes slices. The daily thermal output of the solar dryer is given as in equation 1 (Sujata *et al.,* 2012):

$(Qu)_{daily}$ = moisture evaporated (kg) × Latent heat of evaporation (J/kg)

$$= \frac{\left(M_R \times 2.26\times10^6\right)}{\left(3.6\times10^6\right)} Kwh = 4.3595\text{kwh}$$

… (1)

Therefore, annual thermal output of the dryer, E_{atout} is

$$= \text{Daily thermal output of the dryer (kWh)} \times \frac{N_c}{2}$$

…(2)

where:

N_c is the number of clear days in a year

Amount saved annually $= E_c \times$ annual thermal output of dryer, kwh

…(3)

where:

E_c is unit cost of electricity (#26.93/kwh for domestic consumption, Jos Electricity Distribution Company).

The results of the annual thermal output of the dryer, amount saved annually and for the life cycle of the system is computed and given in Table 1.

Net Present Value (P_{NPV})

Let P_i be the initial investment, R_m is operational and maintenance expenses per year, and R_p is aluminium wire mesh replacement cost in every five years to prevent contamination of dried product, n is life of the solar dryer, S is salvage value of the dryer at the end of the life and CF is net cash flow at the end of each year.

Cash-flow

If 'i' is annual rate of interest in fraction, then the net present value, P_{NPV} can be expressed as Tiwari (2002):

$$P_{NPV} = \left[P_i + R_m \times \left(\frac{(1+i)^n - 1}{i(1+1)^n} \right) + R_p \left\{ \left(\frac{1}{(1+i)^5} \right) + \left(\frac{1}{(1+i)^{10}} \right) + \ldots\ldots. \right\} - S \times \left(\frac{1}{(1+i)^n} \right) \right] \quad \ldots(4)$$

For life of the system to be 10 years, then equation (4) becomes:

$$P_{NPV} = \left[P_i + R_m \times \left(\frac{(1+i)^{10} - 1}{i(1+i)^{10}} \right) + R_p \left\{ \left(\frac{1}{(1+i)^5} \right) \right\} - S \left(\frac{1}{(1+i)^{10}} \right) \right] \quad \ldots(5)$$

Annual Income, Cash flow (CF)

Cost of fresh tomatoes for drying per batch = 120

Weight of dried product per batch = 0.5558kg

Weight of dried product per year, W_T = $0.5558 \times \frac{N_c}{2}$ ... (6)

Average cost of dried tomatoes slices per kg in Bauchi central market = #350 Annual income, I= $W_T \times 350$ ...(7)

S is salvage value of the dryer at the end of its life which is assume to be 2.5% of the initial investment = #1,147.5

Annualized uniform cost, Unacost (R)

Unacost (R) = $P_{NPV} \times F_{PR,i,n}$

$$= P_{NPV} \times \left[\frac{i(1+i)^n}{(1+i)^n - 1} \right]$$

...(8)

According to Tiwari (2002), annualized uniform cost, Unacost (R) is defined as the product of net present value of the system and capital recovery factor (CRF) and can be written as:

Unacost (R) =P_{NPV} × Capital recovery factor (CRF)

The Capital recovery factor (CRF) is expressed as:

$$CRF = F_{PR,i,n} = \left[\frac{i(1+i)^n}{(1+i)^n - 1} \right]$$

...(9)

Cost of drying (C_g)

If Mp is the dried product output per year, kg then cost of drying, C_g is evaluated according to Tiwari (2002) as:

Cost of drying (#/kg) = Unacost, R (#)/Dried product output per year, M_p (kg) ...(10)

Payback Period (n_p)

Payback period is the time usually in years required to recover the investment costs. If it is assume that net cash flow, CF remains the same throughout the life cycle of the system, then net present value (P_{NPV}) can be expressed as Tiwari and Tiwari (2007):

$$P_{NPV} = CF \times F_{RP,i,np} = CF\left[\frac{(1+i)^{n_p}-1}{i(1+1)^{n_p}}\right]$$
…(11)

or

$$(1+i)^{n_p} = \left[\frac{CF}{CF-iP_{NPV}}\right]$$
…(12)

or

$$n_p = \frac{In\left[\frac{CF}{CF-iP_{NPV}}\right]}{In(1+i)}$$
…(13)

Calculation procedure

The initial investment, P_i for the solar dryer is #45,900. Equations 4 and 8 were used to compute the net present value P_{NPV} and Unacost, R respectively for different interest rates of 2.5, 5 and 10% with the life of solar dryer as 10 years and the results are given in Table 3 while equations 13 and 10 have been used to determine the payback period, n_p and cost of drying C_g, respectively for different number of clear days, N_C and the results are given in Table 4. The assumption for the interest rate which ranges from 2.5 to 10% depends on obtaining loans from local cooperatives who lend money to its members and non members in the North-Eastern Nigeria at a low interest rate.

Result

Table 1: **Annual Thermal Outputs, Amount Saved Annually and Life Cycle**

S/No	N_c	Annual thermal outputs, E_{atout} (kwh)	Amount saved annually (#)	Amount saved for 10 years (#)
1	300	653.92	17610.33	176103.30
2	270	588.53	15849.11	158491.10
3	240	523.14	14088.16	140881.60
4	210	457.74	12326.93	123269.30

Table 2: **Net Present Value and Unacost of the Dryer for Ten Years Life (n=10 Years)**

P_i (#)	S (#)	R_p, (#)	i, (%)	$P_{NPV,}$ (#)	R, (#)
45900	1147.5	550	2.5	45489	5197
			5	45626	5905
			10	45799	7451

Table 3: **Net Annual Cash Flow, Pay Back Period, Cost of Drying, Annual Thermal Output and Amount Saved Annually for system with heat storage unit.**

P_{NPV}	i, (%)	R, (#)	N_C	Number of drying batches	M_P (kg)	CF (#)	Payback period, n_p	C_g (#/kg)
45489	2.5	5197	300	150	83	19516	2.42	63
			270	135	75	17564	2.71	69
			240	120	67	15613	3.05	78
			210	105	58	13661	3.51	90
45626	5	5905	300	150	83	19516	2.54	71
			270	135	75	17564	2.84	79
			240	120	67	15613	3.23	88
			210	105	58	13661	3.74	102
45799	10	7451	300	150	83	19516	2.81	89
			270	135	75	17564	3.16	99
			240	120	67	15613	3.64	111
			210	105	58	13661	4.28	128

DISCUSSION

The results for annual thermal output, amount saved annually and for system life cycle are show in table 1 while the number of drying batches that could be allow as a result of clear days in a year, dryer annual output, payback periods and cost of drying with variable parameters like net annual cash flow and annual interest rate are shown in table 3. It can be seen in table 3 that the payback period increases as the annual cash flow decreases as a result of reduction in number of clear days. In addition, it is noted that the interest rate have effect on payback period at most especially at low annual net cash flow. Savings from the use of solar systems as against or systems which uses electricity shows a positive trend as show in table 1. The cost of drying increases as the interest rate increases. This will significantly affect farmers ability to invest into such renewable energy devices if they are borrowing at a higher interest rate mostly from commercial banks thus, discouraging the use of renewable energy systems.

CONCLUSION AND RECOMMENDATIONS

The indirect mode natural convection solar dryer was constructed with locally available materials at an affordable cost. A substantial percentage of drying time was reduced as a result of incorporating a heat storage bed as well as superior quality of dried product over open sun method. Though, the net annual cash flow is relatively low, moderate to bigger drying systems would gave better returns and prevent wastage of fresh tomatoes which supply is in excess of its demand during the harvest time. It is therefore recommended that government should support rural farmers with renewable energy systems to promote food sufficiency.

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