

Performance of Solar Cabinet Dryer Utilizing Thermosyphon Water Heater



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Abstract The model of optimal design of solar assisted cabinet dryer was formulated for green banana. The simulation model is composed of three systems: one for the water collector, one for the air collector and other for the drying cabinet. Economic and manufacturability factors were considered in the optimal design. A solar cabinet banana dryer utilizing a thermosyphon solar water heater as the main source of heat and a solar air heater as auxiliary source was tested with green Cavendish variety of banana as the drying specimen. From period April to June the experiment was conducted in the rooftop to ensure good solar irradiance. It was found out the solar water collector can generate a maximum water temperature of 60 °C and a drying chamber temperature of 50 °C during noon and at clear sky condition. Also the air heater generates about 40 °C. The temperature profile of the drying chamber resembles a sine curve. The temperature profile was lower than that of the mathematical model. These were contributed from the construction of the solar heater but overall performance.

Keywords Air collector · Banana solar dryer · Cabinet dryer · Thermosiphon · Water heater

1 Introduction

1.1 Background of the Study

In the Philippines, Region XI is the leading producer of Cavendish Banana. The majority of these plantations are independent small-scale banana growers. Banana produce is exported to the Middle East, Japan and China.

Low quality bananas are peeled, sliced and sun dried. These dried bananas are the raw materials for the growing banana flour industry and banana feed meal for the livestock industry. The drying process is done chiefly through sun drying mostly on

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roadsides, pavement, GI sheets, stone slabs and concrete basketball courts [1]. Dried products are subject to contamination by extraneous materials such as sand, stones, soils, leaves and incursion by rats, insects and animal excreta [2]. During the rainy season, discoloration and spoilage are inevitable [3]. Flour mills can acquire large scale drying technologies but banana growers and farmers don't have this alternative and only use sun drying.

There are three categories of drying methods including sun drying, solar drying and mechanical drying. Sun drying and solar drying utilizes sun's energy. Solar dryers, compared to sun drying can generate higher air temperature and lower relative humidity. Mechanical dryer uses energy resources such as biomass, fossil fuel and electricity [4].

Solar dryers are generally classified based on whether the product is directly exposed to insolation, the mode of air flow through the dryer, and the air temperature circulated to the drying chamber. In direct dryers, the crop is exposed to the sun but, in indirect dryers, the crop is placed in an enclosed drying chamber and thus shielded from insolation [5]. Indirect dryers can be either passive (natural convection) or active (forced convection) dryer. Solar collectors are directly coupled with the dryer. A greenhouse dryer is a type of direct solar dryer. These dryers are either dome or flat roof structures [6]. Dome type can have maximized the global solar radiation while the flat roof structure take advantage with good mixing of hot air. Solar dryers can utilized a thermal storage system and water has a good thermal storage properties [7]. Water heaters were employed as heat source for indirect dryers [8]. It consist of a drying cabinet, heat exchanger, water heater solar collector and a heat storage tank.

Čipliene, Novošinskas, Raila, and Zvicevičius [9] made an experimental dryer that utilized two types of solar collectors. The air heater used for direct heating of the drying agent and the flat plate solar collector accumulated the converted energy and stored it in the tank. Daghig and Shafieian, [10] utilized a heat-pipe evacuated tube solar dryer with heat recovery system and water as the heating medium.

The alternative drying technique to be described in this study is an indirect solar dryer. The dryer will utilize two types of collectors, and a thermosyphon solar water heater was used to supply heat in the drying chamber by a heat exchanger. Supply air was preheated in solar air heaters. However, available water heaters such as the water-in-glass evacuated tube solar heaters and the heat pipe solar heaters were expensive and were not appropriate for small-scale farmers. Thus study investigates the actual performance of the solar dryer and compares it to the simulated result.

1.2 Design of the Solar Cabinet Dryer

Indirect solar dryers are those in which the crops are placed in an enclosed drying cabinet, thereby being shielded from direct exposure to solar radiation. An indirect solar dryer basically consists of two major components: an air heater, which is used to raise the temperature of the drying air and a drying chamber which is the enclosure that accommodates the crops. Kwendakwema [11] designed and tested an indirect

forced air solar food dryer consisting of flat-plate solar collector, drying cabinet and a brick heat storage unit. This solar cabinet dryer consist of three major parts: the solar water heater; the solar air heater; and the drying cabinet.

The dryer utilized a thermosyphon solar water heater. The 0.84 m³ flat plate solar collector is made of six-1.4–10 mm copper tubes and 20 mm-riser and header. A 0.29 mm aluminum plate acts as the solar absorber, painted black, molded to the copper tube with a silicon adhesive to eliminate air pockets. The collector is covered with 2 layer 5 mm glass panel and insulated with 25 mm thick mineral wool. The solar air heaters consist of two solar collectors with a total area of 1.5 m³. The force convection collector utilized a used car air conditioning blower.

The drying cabinet consists of 4 drying trays. The dimension of the tray is 40 × 50 cm. A heat exchanger made of an old car radiator with the radiator fan serves as a circulating fan.

2 Theoretical Mathematical Model

A mathematical model was developed to simulate the performance of the solar water heater, the air collector and the drying cabinet.

2.1 Solar Collector

The mathematical model of the solar heater was the energy balance of the collector taking into consideration a steady-state condition. Under steady-state conditions, the useful energy output of the collector [12]

$$Q_u = A_c [S - U_L (T_{pm} - T_a)] \quad (1)$$

and can be expressed in terms of fluid inlet temperature and the collector removal factor

$$Q_u = A_c F_R [S - U_L (T_i - T_a)] \quad (2)$$

the collector removal factor can be expressed as

$$F_R = \frac{\dot{m} C_p}{A_c U_L} \left[1 - \exp \left(- \frac{A_c U_L F'}{\dot{m} C_p} \right) \right] \quad (3)$$

The collector efficiency factor F' is the ratio of actual useful energy gain to the useful gain of the collector absorbing surface at the local fluid temperature. This collector efficiency factor is constant at a particular collector design. This research collector design, the collector efficiency of the water heater collector is,

$$F' = \frac{1}{\frac{WU_L}{\pi Dh} + \frac{WU_L}{C_{bond}} + \frac{W}{D+(W-D)F}} \tag{4}$$

$$F = \frac{\text{Tanh } m(W - D)/2}{m(W - D)/2} \tag{5}$$

and for the air heater collector, is

$$F' = \frac{1}{1 + \frac{U_{L1}}{h_1 + \frac{1}{\frac{1}{h_2} + \frac{1}{h_r}}}} \tag{6}$$

where

$$h_r = \frac{\sigma(T_1^2 + T_2^2)(T_1 + T_2)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \tag{7}$$

the mean fluid temperature and the mean plate temperature are expressed as

$$T_{fm} = T_{fi} + \frac{Q_u/A_c}{F_R U_L} (1 - F''') \tag{8}$$

and

$$T_{pm} = T_{fi} + \frac{Q_u/A_c}{F_R U_L} (1 - F_R) \tag{9}$$

The collector’s overall heat transfer coefficient can be determined by adding the top loss coefficient and the bottom coefficient. The bottom coefficient is easily determined by conduction heat transfer analysis and in some cases of air heaters, convection analysis is also considered. The top loss heat transfer coefficient empirical equation develop by Klien [4] is useful for hand and computer computations.

$$U_t = \left(\frac{N}{\frac{C}{T_{pm}} \left[\frac{(T_{pm} - T_a)}{(N+f)} \right]^e} + \frac{1}{h_w} \right) + \frac{\sigma(T_{pm} + T_a)(T_{pm}^2 + T_a^2)}{\frac{1}{\varepsilon_p + 0.00591Nh_w} + \frac{2N+f-1+0.133\varepsilon_p}{\varepsilon_g} - N} \tag{10}$$

where

$$\begin{aligned} f &= (1 + 0.089h_w - 0.1166h_w\varepsilon_p)(1 + 0.078866N) \\ C &= 520(1 - 0.000051\beta^2) \text{ for } 0 < \beta < 70 : \text{ for } 70 < \beta < 90. \text{ use } \beta = 70 \\ e &= 0.4330(1 - 100/T_{pm}) \end{aligned}$$

The fluid motion of the thermosyphon developed from the momentum balance of the collector tube[13].

$$\frac{d\dot{V}}{dt} = -B - F\dot{V} \quad (11)$$

the “bouyancy” term B is expressed as

$$B = \frac{\frac{\pi g}{4\rho} \sum_{k=1}^n \rho_k L_k \sin\theta_k}{\sum_{k=1}^n \frac{L_k}{D_k^2}} \quad (12)$$

the “frictional” term F is expressed as

$$F = \frac{\frac{128\mu}{4\rho} \sum_{k=1}^n \frac{(L_{eq})_k L_k}{D_k^3}}{\sum_{k=1}^n \frac{L_k}{D_k^2}} \quad (13)$$

3 Experimentatal Setup

3.1 Solar Cabinet Dryer

The solar dryer consists of three heating systems integrated into one; a water heater collector, an air heater, and a drying chamber. The cabinet dryer was set up on the rooftop to minimize the shades of trees. An open ground was set up was not possible because of the restriction of data logging equipment. The collector was facing north. Both collectors are inclined 30° with the horizontal (See Fig. 1).

3.2 Data Collection

Data collection was done with DATATAKER 80 series. The temperature was taken by a type k thermocouple placed at entrance and exit of each collector and heat exchanger. Calibration of these thermocouples were made using the boiling and ice points of water. Instrument accuracy ($\pm 1\%$) was determined. Solar radiation was measured by a pyranometer (Kipp and Zonen model CP3 accuracy $\pm 5\%$). The weight of the banana was measured by a load cell. Measurements signals from the thermocouple, pyranometer and load cell (accuracy $\pm 5\%$) were recorded every 15 s by a 15-channel data logger (DATATAKER DT80 series 3). The air velocity was measured manually using a hot wire anemometer (Lutron AM4204 accuracy $\pm 5\%$).

The experiment runs from 7:00 AM to 6:00 PM at clear sky conditions and cloudy conditions. Green bananas were peeled, washed and sliced into 2 mm thick slices. A 5 kg sample were evenly distributed to the four drying trays. The tank of the water heater serves as energy storage.



Fig. 1 The solar cabinet Dryer

3.3 Simulation

The solution of the mathematical model is simulated in MS Excel. An Excel Macro was created using the Visual Basic features of Excel to solve the performance and characteristics of the collector. A temperature profile was created using the actual isolation data from the data logger. Using the excel spreadsheets, the numerical calculation of Eq. 10 determines the overall heat transfer coefficient.

4 Results

The experiment was performed during summer from April 2012-June 2012. Experiment was taken out during a clear sky and cloudy sky conditions. The insolation during the clear sky and cloud sky, respectively. These insolation values were used to determine the projected collector mean plate temperature and the collector mean fluid temperature (see Fig. 2 and Fig. 3).

Results of the simulation and the actual data collected was compared. Using the Normalized root-mean-square deviation (NRMSD), the two data sets were compared [13]. During the clear sky simulation and experimental setup (Fig. 4), the performance of the collector was compared to the simulation results and the actual data from the logger. The figure clearly show that the simulated condition were higher than the

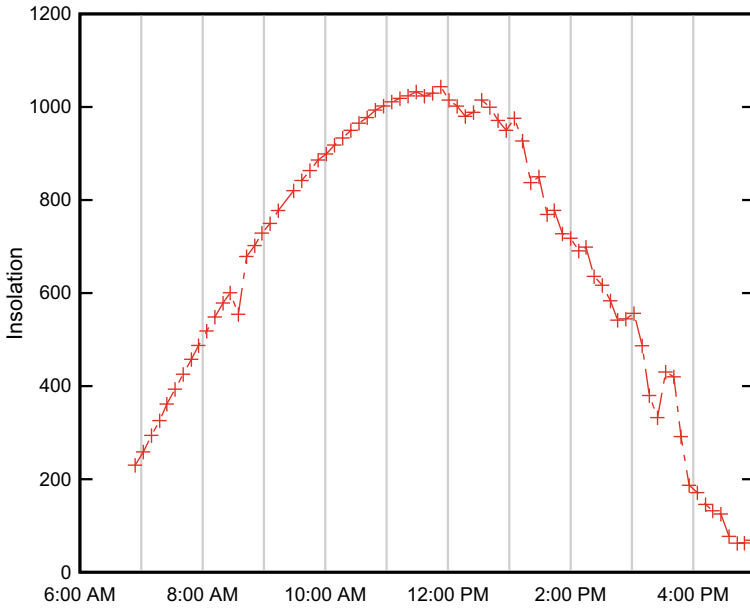


Fig. 2 Clear sky solar insolation

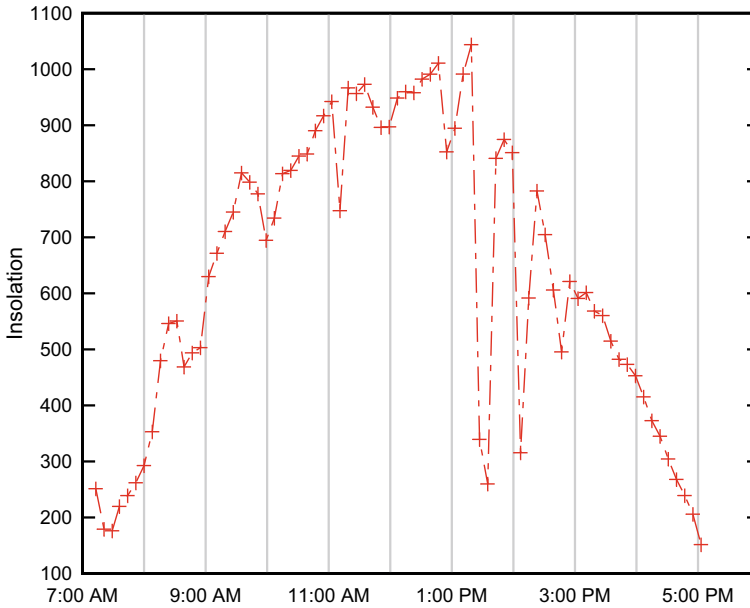


Fig. 3 Cloudy sky insolation

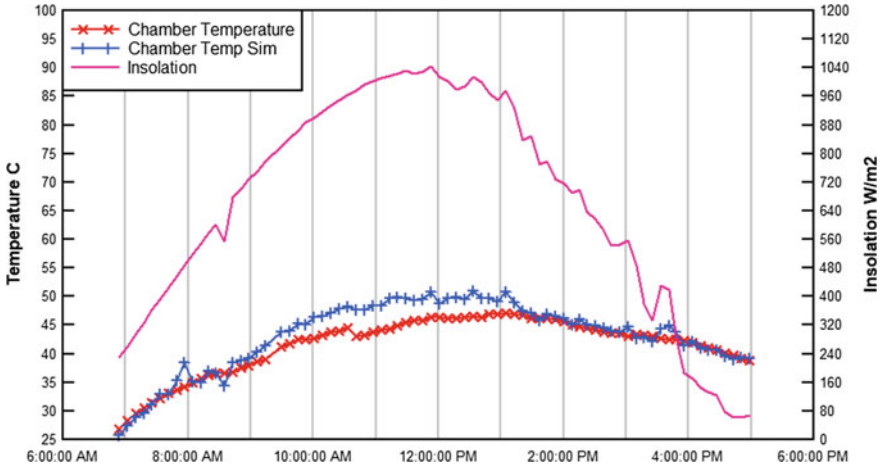


Fig. 4 Chamber temperature vs. simulation result during clear sky condition

experimental value. Moreover, shown in Fig. 5 is the cloudy sky simulation and experimental setup.

The temperature profile of the water heater at clear sky condition was compared to the simulated temperature (see Fig. 6). Both inlet and outlet temperature shows an NRMSD value of 8 and 8% respectively. Moreover, temperature during the intermittent cloudy condition was compared to the simulated temperature and shows both inlet and outlet temperature shows NRMSD value of 30 and 18% respectively (see Fig. 7).

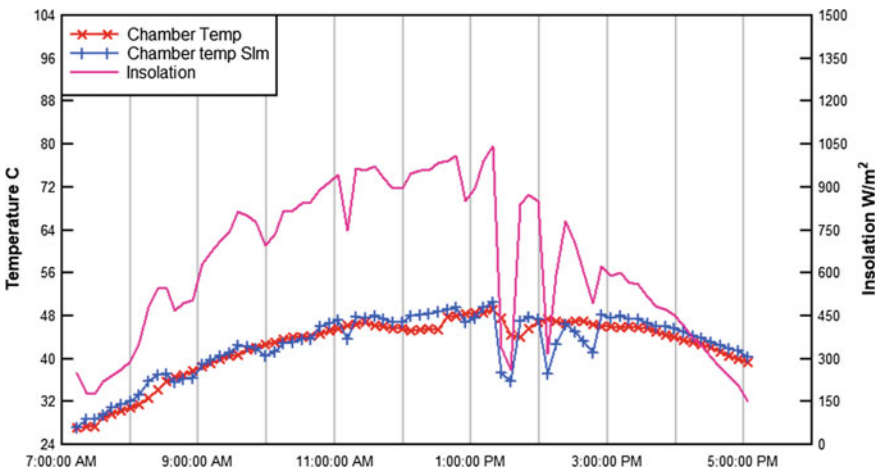


Fig. 5 Chamber temperature vs. simulation result during cloudy condition

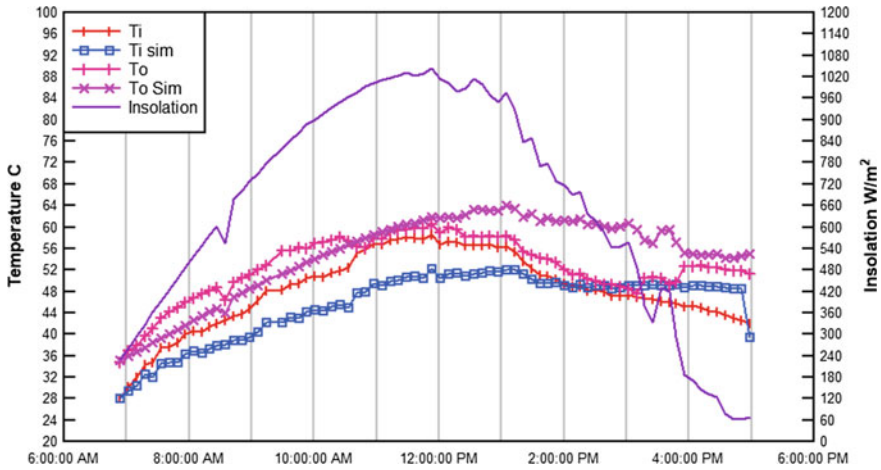


Fig. 6 Clear sky temperature profile of water heater vs simulation results

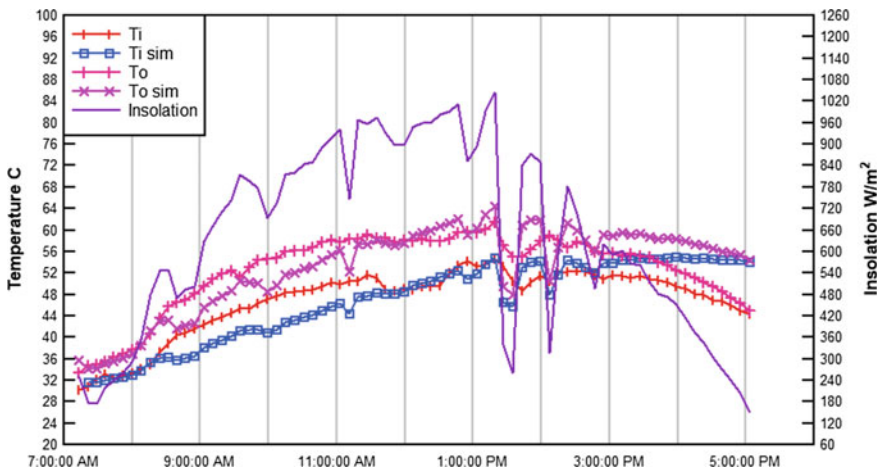


Fig. 7 Cloudy sky temperature profile of water heater vs simulation results

5 Conclusion and Recommendation

The experimental solar dryer performance was evaluated. Solar insolation and chamber temperature was monitored during testing. Actual temperatures were below the simulated values may points to several factors in the construction of the dryer. The maximum water temperature and the chamber temperatures were 56 and 48 °C. The results can be applied in the performance of the water heater and the cabinet dryer when considering the temperature generated by the collectors and the heat exchanger in general. These temperatures are sufficient enough for low temperature

drying of food products. The solar dryer efficiency when intermittent cloud cover was observed was comparable with the efficiency on clear sky conditions. This is an indication that the heat storage is dual collector system that address the problem of variability of the solar radiation.

An opportunity on the design of the collector, a study may have been conducted to investigate the behavior of the solar water heater during high solar radiation and the temperature between the inlet and outlet on the water collector. A study on the thermal storage capacity of the liquid water and considered as a secondary heat source during nighttime extended drying hours.

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