Design and Construction of a Domestic Passive Solar Food Dryer

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Abstract

The solar drying system utilizes solar energy to heat up air and to dry any food substance loaded, which is not only beneficial in that it reduces wastage of agricultural produce and helps in preservation of agricultural produce, but it also makes transportation of such dried produce easy and promotes the health and welfare of the people. This paper presents the design and construction of a domestic passive solar food dryer. The dryer is composed of solar collector (air heater) and a solar drying chamber containing rack of four cheese cloth (net) trays both being integrated together. The air allowed in through air inlet is heated up in the solar collector and channeled through the drying chamber where it is utilized in drying (removing the moisture content from the food substance or agricultural produce loaded). The design was based on the geographical location which is Abeokuta and meteorological data were obtained for proper design specification. Locally available materials were used for the construction, chiefly comprising of wood (gmelina), polyurethane glass, mild steel metal sheet and net cloth for the trays.

Keywords

Solar drying; Solar collector; Agriculture produce; Optimum temperature.

Introduction

Drying is an excellent way to preserve food and solar food dryers are appropriate food preservation technology for sustainable development [1]. Drying was probably the first ever food preserving method used by man, even before cooking. It involves the removal of moisture from agricultural produce so as to provide a product that can be safely stored for longer period of time.

"Sun drying" is the earliest method of drying farm produce ever known to man and it involves simply laying the agricultural products in the sun on mats, roofs or drying floors. This has several disadvantages since the farm produce are laid in the open sky and there is greater risk of spoilage due to adverse climatic conditions like rain, wind, moist and dust, loss of produce to birds, insects and rodents (pests); totally dependent on good weather and very slow drying rate with danger of mould growth thereby causing deterioration and decomposition of the produce. The process also requires large area of land, takes time and highly labour intensive [2].

With cultural and industrial development, artificial mechanical drying came into practice, but this process is highly energy intensive and expensive which ultimately increases product cost [2]. Recently, efforts to improve "sun drying" have led to "solar drying".

In solar drying, solar dryers are specialized devices that control the drying process and protect agricultural produce from damage by insect pests, dust and rain. In comparison to natural "sun drying", solar dryers generate higher temperatures, lower relative humidity, lower product moisture content and reduced spoilage during the drying process. In addition, it takes up less space, takes less time and relatively inexpensive compared to artificial mechanical drying method. Thus, solar drying is a better alternative solution to all the drawbacks of natural drying and artificial mechanical drying [2].

The solar dryer can be seen as one of the solutions to the world's food and energy crises. With drying, most agricultural produce can be preserved and this can be achieved more efficiently through the use of solar dryers.

Solar dryers are a very useful device for:

- Agricultural crop drying.
- Food processing industries for dehydration of fruits and vegetables.
- Fish and meat drying.

- Dairy industries for production of milk powder.
- Seasoning of wood and timber.
- Textile industries for drying of textile materials, etc.

Thus, the solar dryer is one of the many ways of making use of solar energy efficiently in meeting man's demand for energy and food supply.

Some Background to the Concept

Attempts to Harness Solar Energy

The idea of using solar energy to produce high temperature dates back to ancient times. The solar radiation has been used by man since the beginning of time for heating his domicile, for agricultural purposes and for personal comfort [3]. Reports abound in literature on the 18th century works of Archimedes on concentrating the sun's rays with flat mirrors; Antoine Lavoisier on solar furnace; Joseph Priestly on concentrating rays using lens [3]. In the 19th century, development of solar distillation unit covering 4750sq meters of land, operated for 40 years and, producing 6,000 gallons of water from salt water per day has been reported. Also, John Ericson's work on conversion of solar energy into mechanical energy through a device, which produced 1hp (746 W) for each 9.3m^2 of collecting surface has also been reported [3].

Modern research on the use of solar energy started during the 20th century. Developments include the invention of a solar boiler, small powered steam engines and solar battery, but it is difficult to market them in competition with engines running on inexpensive gasoline [3,4]. During the mid 1970's shortages of oil and natural gas, increase in the cost of fossil fuels and the depletion of other resources stimulated efforts in the United States to develop solar energy into a practical power source. Thus, interest was rekindled in the harnessing of solar energy for heating and cooling, the generation of electricity and other purposes.

Capturing Solar Energy

Solar radiation can be converted either into thermal energy (heat) or into electrical energy. This can be done by making use of thermal collectors for conversion into heat energy or photovoltaic collectors for conversion into electrical energy. Two main collectors are used to capture solar energy and convert it to thermal energy, these are flat plate collectors and concentrating collectors [3]. In this paper, emphasis is laid much on the flat plate collectors which are also known as non-focusing collectors.

Importance of Solar Dried Food

For centuries, people of various nations have been preserving fruits, other crops, meat and fish by drying. Drying is also beneficial for hay, copra, tea and other income producing non-food crops [5]. With solar drying being available everywhere, the availability of all these farm produce can be greatly increased. It is worth noting that until around the end of the 18th century when canning was developed, drying was virtually the only method of food preservation [5].

The energy input for drying is less than what is needed to freeze or can, and the storage space is minimal compared with that needed for canning jars and freezer containers. It was further stated that the nutritional value of food is only minimally affected by drying [6]. Also, food scientists have found that by reducing the moisture content of food to 10 to 20%, bacteria, yeast, mold and enzymes are all prevented from spoiling it. Microorganisms are effectively killed when the internal temperature of food reaches 145°F [6]. The flavour and most of the nutritional value of dried food is preserved and concentrated [1]. Dried foods do not require any special storage equipment and are easy to transport [1]. Dehydration of vegetables and other food crop by traditional methods of open-air sun drying is not satisfactory, because the products deteriorate rapidly [5].

Studies showed that food items dried in a solar dryer were superior to those which are sun dried when evaluated in terms of taste, colour and mould counts [7,8]. Solar dried food are quality products that can be stored for extended periods, easily transported at less cost while still providing excellent nutritive value. This paper therefore presents the design and construction of a domestic passive solar food dryer.

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Material and Method

General Description of the Domestic Passive Solar Food Dryer

The most commonly seen design types are of cabinet form (wooden boxes with glass cover), some types are even improved making use of cardboard boxes and transparent nylon or polythene.

For the design being considered, the greenhouse effect and thermosiphon principles are the theoretical basis. There is an air vent (or inlet) to the solar collector where air enters and is heated up by the greenhouse effect, the hot air rises through the drying chamber passing through the trays and around the food, removing the moisture content and exits through the air vent (or outlet) near the top of the shadowed side.

The hot air acts as the drying medium, it extracts and conveys the moisture from the produce (or food) to the atmosphere under free (natural) convection, thus the system is a passive solar system and no mechanical device is required to control the intake of air into the dryer.

The solar food dryer consists of two major compartment or chambers being integrated together:

- The solar collector compartment, which can also be referred to as the air heater.
- The drying chamber, designed to accommodate four layers of drying trays made of net cloth (cheese cloth) on which the produces (or food) are placed for drying.

Materials Used

The following materials were used for the construction of the domestic passive solar dryer:

- Wood (gmelina) - as the casing (housing) of the entire system; wood was selected being a good insulator and relatively cheaper than metals.
- Glass - as the solar collector cover and the cover for the drying chamber. It permits the solar radiation into the system but resists the flow of heat energy out of the systems.
- Mild steel sheet of 1mm thickness (dimension 80cm × 60cm) painted black with tar - for absorption of solar radiation.
- Net cloth (cheese cloth) and wooden frames for constructing the trays.
- Nails and glue as fasteners and adhesives.
- Insect net at air inlet and outlet - to prevent insects from entering into the dryer.

- Hinges and handle for the dryer's door.
- Paint (black and grey).

Design Consideration

1. Temperature - The minimum temperature for drying food is 30°C and the maximum temperature is 60°C, therefore. 45°C and above is considered average and normal for drying vegetables, fruits, roots and tuber crop chips, crop seeds and some other crops [5].
2. The design was made for the optimum temperature for the dryer. T_0 of 60°C and the air inlet temperature or the ambient temperature T1 = 30°C (approximately outdoor temperature).
3. Efficiency - This is defined as the ratio of the useful output of a device to the input of the device.
4. Air gap - It is suggested that for hot climate passive solar dryers, a gap of 5 cm should be created as air vent (inlet) and air passage.
5. Glass and flat plate collector – It suggested that the glass covering should be 4-5 m thickness. In this work, 4mm thick transparent glass was used. He also suggested that the metal sheet thickness should be of 0.8 – 1.0 m thickness; here a mild steel of 1.0mm thickness was used. The glass used as cover for the collector was 60 × 60cm^2 [9].
6. Dimension – It is recommended that a constant exchange of air and a roomy drying chamber should be attained in solar food dryer design, thus the design of the drying chamber was made as spacious as possible of average dimension of 60 × 57 × 55cm with air passage (air vent) out of the cabinet of 60 × 5cm^2. The drying chamber was roofed with glass of 60 × 60 cm tilted at the same angle with that of the solar collector (17.11°). This is to keep the temperature within the drying chamber fairly constant due to the greenhouse effect of the glass.
7. Dryer Trays - Net cloth was selected as the dryer screen or trays to aid air circulation within the drying chamber. Four trays were made having wooden edges. The tray dimension is 50 × 50cm of 2.5cm × 2.5cm wooden sticks used as frame.

The design of the dry chamber making use of wooden wall sides and a glass top (tilted) protects the food to be placed on the trays from direct sunlight since this is undesirable and tends to bleach colour, removes flavour and causes the food to dry unevenly [5].

Design Calculations

1. Angle of Tilt (β) of Solar Collector/Air Heater.

It states that the angle of tilt (β) of the solar collector should be

$\beta = 10^0 + \text{lat } \phi$ [9] (1)

were lat ϕ is the latitude of the collector location, the latitude of Abeokuta where the dryer was designed is latitude 7.11^0N.

Hence, the suitable value of β use for the collector:

$\beta = 10^0 + 7.11^0 = 17.11^0$

2. Insolation on the Collector Surface Area.

A research obtained the value of insolation for Abeokuta i.e. average daily radiation H on horizontal surface as; [10]

$H = 978.69 W/m^2$

and average effective ratio of solar energy on tilted surface to that on the horizontal surface R as;

$R = 1.0035$

Thus, insolation on the collector surface was obtained as

$I_c = H_T = HR = 978.69 \times 1.0035 = 982.11 W/m^2$ (2)

3. Determination of Collector Area and Dimension.

The mass flow rate of air M_a was determined by taking the average air speed V_a = 0.15m/s.

The air gap height was taken as 5cm = 0.05m and the width of the collection assumed to be 60cm = 0.6m.

Thus, volumetric flow rate of air $V'_a = V_a \times 0.05 \times 0.6$

$V'_a = 0.15 \times 0.05 \times 0.6 = 4.5 \times 10^{-3} m^3/s$

Thus mass flow rate of air:

$M_a = v_a \rho_a$ (3)

Density of air ρ_a is taken as $1.28 kg/m^3$

$M_a = 4.5 \times 10^{-3} \times 1.28 = 5.76 \times 10^{-3} kg/s$

Therefore, area of the collector A_C

$A_C = (5.76 \times 10^{-3} \times 1005 \times 30)/(0.5 \times 982.11) = 0.3537 m^2$

The length of the solar collector (L) was taken as;

$L = A_c/B = 0.3537/0.6 = 0.59 m$

Thus, the length of the solar collector was taken approximately as 0.6m.

Therefore, collector area was taken as $(0.6 \times 0.6)^2 = 0.36m^2$

4. Determination of the Base Insulator Thickness for the Collector.

The rate of heat loss from air is equal to the rate of heat conduction through the insulation. The following equation holds for the purpose of the design.

$$Fm_aC_p (T_0 - T_i) = K_a(T_a - T_a)/t_b \quad (4)$$

$K = 0.05Wm^{-1}K^{-1}$ which is the approximate thermal conductivity for polyurethane [11].

$F = 10\% = 0.1$

$T_0 = 60^oC$ and $T_i = T_a = 30^oC$ approximately

$m_a = 5.76 \times 10^{-3}Kgs^{-1}$

$C_p = 1005JKg^{-1}K^{-1}$

and $A_c = 0.36m^2$

$t_b =[0.05 \times 0.36 \times (60\text{-}30)]/[0.1\times5.76\times10^{-3}\times1005\times(60\text{-}30)] = 0.0311 = 3.11cm$

For the design, the thickness of the insulator was taken as 7cm. The side of the collector was made of wood, the loss through the side of the collector was considered negligible.

5. Determination of Heat Losses from the Solar Collector (Air Heater).

Total energy transmitted and absorbed is given by

$$I_cA_c\tau_\alpha = Q_u + Q_L + Q_s \quad (5)$$

where Q_s is the energy stored which is considered negligible therefore,

$$I_cA_c\tau_\alpha = Q_u + Q_L \quad (6)$$

Thus Q_L the heat energy losses

$$Q_L = I_cA_c\tau_\alpha - Q_u \quad (7)$$

Since

$$Q_u = m_aC_p (T_0 - T_i) = m_aC_p\Delta T \quad (8)$$

and

$$Q_L = U_LA_c\Delta T \quad (9)$$

then

$$U_LA_c\Delta T = I_cA_c\tau_\alpha - m_aC_p\Delta T \quad (10)$$

$$U_L = (I_cA_c\tau_\alpha - m_aC_p\Delta T)/(A_c\Delta T) \quad (11)$$

α was taken as 0.9 and $\tau = 0.86$

$T_a = 0.774$

$U_L = (982.11\times0.36\times0.774 - 5.76\times10^{-3}\times1005\times30)/(0.36\times30) = (273.66\text{-}173.66)/10.8$

$U_L = 9.26 W/m^2 °C$

Therefore,

$Q_L = 9.26 \times 0.36 \times 30 = 100.01 W$

This heat loss includes the heat loss through the insulation from the sides and the cover glass.

Construction

The solar food dryer was constructed making use of locally available and relatively cheap materials. Since the entire casing is made of wood and the cover is glass, the major construction works is carpentry works (joinery).

The following tools were used in measuring and marking out on the wooden planks:

- Carpenter's pencil.
- Steel tapes (push-pull rule type).
- Steel meter rule.
- Vernier caliper.
- Steel square.
- Scriber.

The following tools were also used during the construction:

- Hand saws (crosscut saw and ripsaw).
- Jack plane.
- Wood chisel.
- Mallet.
- Hammer.
- Pinch bar and pincers.

The construction was made with simple butt joints using nails as fasteners and glue (adhesive) where necessary. The construction was sequenced as follows for the wood work.

- Marking out on the planks to cut into desired shape.
- Cutting out the already marked out parts.
- Planning of cut out parts to smoothen the surfaces.

- Joining and fastening of the cut out parts with nails and glues.

The metal sheet used was mild steel of 1mm thickness. It was cut to the size of 80 × 60cm to minimize the top heat loss. It was painted black with tar for maximum absorption and radiation of heat energy. The metal sheet, together with the insulator of 7cm thickness, was placed inside the air heater (solar collector) compartment.

The glass was cut into size of 60 × 60cm size and two of these were required. One as the solar collector's cover, and the other, as the drying cabinet cover. The glass used was clear glass with 4 mm thickness.

The trays were made with wooden frames and net cloth to permit free flow of air within the drying cabinet (chamber). Four trays were used with average of 10cm spacing arranged vertically one on top of the other, the tray size was 56 × 52cm.

The interior of the solar food dryer was painted black with tar to promote adsorption of heat energy while the exterior was painted gray to minimize the adverse effects of weather and insect attack on the wood and also for aesthetic appeal.

Conclusions

Solar radiation can be effectively and efficiently utilized for drying of agricultural produce in our environment if proper design is carried out. This was demonstrated and the solar dryer designed and constructed exhibited sufficient ability to dry agricultural produce most especially food items to an appreciably reduced moisture level.

Locally available cheap materials were used in construction making it available and affordable to all and sundry especially peasant farmers. This will go a long way in reducing food wastage and at the same time food shortages, since it can be used extensively for majority of the agricultural food crops. Apart from this, solar energy is required for its operation which is readily available in the tropics, and it is also a clean form of energy. It protects the environment and saves cost and time spent on open sun drying of agricultural produce since it dries food items faster. The food items are also well protected in the solar dryer than in the open sun, thus minimizing the case of pest and insect attack and also contamination.

However, the performance of existing solar food dryers can still be improved upon especially in the aspect of reducing the drying time and probably storage of heat energy within the system. Also, meteorological data should be readily available to users of solar products to ensure maximum efficiency and effectiveness of the system. Such information will probably guide a local farmer on when to dry his agricultural produce and when not to dry them.

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