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Design, fabrication and utilization of solar tunnel dryer for different types of food vegetables and medicinal plants

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Abstract: The research was conducted to fabricate and develop an advanced solar tunnel dryer (STD) for the drying of fruits, vegetables and medicinal plants. The system was designed as a portable system for decentralized applications at various sites to satisfy the drying requirements of small farmers and co-operatives. The cross sectional area of the solar tunnel dryer was trapezoidal in shape having 0.1225 m^2 face area, with length and width of four meters and one and half meter respectively. It comprises a collector section (2 m) long and a drying section (2 m long) and one electric powered fan to provide the required air flow rate over the perishable agricultural products to be dried. Transparent polythene cover was used to close the dryer on top side to maintain the steady state air flow within the dryer. It has been observed that the drying air temperature was easily raised by some 8-14°C above the ambient temperature at air velocity ranges 0-1 ms^{-1}. The process curves were found similar to a conventional dryer showing that this dryer can be successfully utilized for the drying of agricultural products using solar energy.

Key words: Dehydration, Solar dryer, Tunnel dryer, Tray dryer, Solar collector, Drying unit, Face area, Psychrometric analysis

Introduction

Drying of fruits and vegetables offers a challenging task due to the different structural characteristics of these products. The removal of water from these products must be accomplished without compromising the physico-chemical properties and quality of the dried products. To obtain the desired quality products, some fundamental concepts associated with food dehydration such as water activity, sorption isotherms and glass transition temperature, among other concepts need to be understood. A selection of appropriate drying methods and systems must be analyzed based on the entire drying process. For example, there is a need to define the types and characteristics of raw materials to be dried, and the specifications of the finished product. Also, the desired production capacity, shape and particle size distribution, and drying characteristics of the product should also be critically assessed. Several dehydration methods and types of dryers are commercially available for drying a wide range of food products. Approximately 100 types of dryers of the more than 400 types reported in the literature. Tang (2003). are being utilized in the industry. These dryers are classified into several categories, based on certain specific criteria (Vega-Mercado *et al.*, 2001). Divided dehydration technologies into four generations: first generation (*i.e* kiln, tray, truck tray, rotary flow conveyor and tunnel); second generation (*i.e.* spray and drum drying); third generation (*i.e.* freeze-dying and osmotic dehydration), and fourth generation (*i.e.* Rrefractance, high-vacuum, fluidization, microwaves, and RF). Nindo and Tang (2007) classified dehydration into four categories, namely, drying strategy, drying medium, method of handling of solids, and mode of heat input. De Graaf et al. (2003) suggested three basic types of drying processes for fruits and vegetables such as sun or solar drying, atmospheric and continuous, sub-atmospheric drying, and low-temperature and low-energy drying process (Abiad *et al.*, 2009).

Regardless of the classifications and categorization of dehydration technologies, the application of a particular drying technique for fruits and vegetables depends on the type of raw material and its characteristics and intended used of the dried material. In most cases, the acceptance of drying methods and designs is highly dependent on the capacity, efficiency, investment cost, operational drying cost, and impact on the environment (Jayasundera, *et al.,* 2011). Drying is usually conducted by vaporizing water in the product. Thus, the latent heat of vaporization must be supplied. Airflow is also required to remove the vapor away from the product. The lower the humidity of hot air supplied to the drying chamber is, the better the drying rate, as the less humid air can carry more moisture from the product surface than the more humid air. Generally, increasing the temperature and velocity shortens the drying time. However, for heat-sensitive products, such as food and pharmaceutical products, high temperature decreases product quality. In this case, drying at low temperature and humidity is required to maintain the fresh color of the product using the desiccant system. Without the use of the desiccant system, high temperature is required to obtain low humidity. The same product dried with different techniques produces different levels of product quality (Mujumdar, 2008). Dehydration is a process that involves the application of heat to remove moisture from fresh fruit and vegetable products (Jaya and Das, 2004). Its primary objective is to reduce microbial activity and deterioration, and to extend the shelf life of the product. Other benefits of dehydration include reduction of weight, which greatly decreases the cost of packaging, handling, storage and transport (Labuza and Altunakar, 2007). Several authors have published books and articles focused on different drying techniques and technologies (Bolland, 2000). The present research describes fundamental concepts related to design and fabrication of advanced and cheap solar tunnel dryer for dehydration of fruits and vegetables (Adhikari, 2009; Kumar, 2015).

The main objective of this research is to design and fabricate of solar tunnel dryer and also evaluate its performance.

Materials and Methods

Solar drying is often differentiated from "sun drying" by the use of equipment to collect the sun's radiation in order to harness the radioactive energy for drying applications. Sun drying is a common farming and agricultural process in many countries, particularly where the outdoor temperature reaches 30^{0}C or higher. In many parts of India, spice crops and herbs are routinely dried. However, weather conditions often preclude the use of sun drying because of spoilage due to dehydration during unexpected rainy days. Furthermore, any direct exposure to the sun during high temperature days might cause case hardening, where a hard shell develops on the outside of the agricultural products, trapping moisture inside. Therefore, the employment of solar dryer taps on the freely available sun energy while ensuring good product quality via judicious control of the radioactive heat. Solar energy has been used throughout the world to dry food products. Such is the diversity of solar dryers that commonly solar-dried products include grains, fruits, meat, vegetables and fish (Farhat, 2004). The three modes of drying are: (i) open sun, (ii) direct and (iii) indirect in the presence of solar energy. The working principle of these modes mainly depends upon the method of solar-energy collection and its conversion to useful thermal energy (Asami *et al.*, 2003).

Basic principles of drying: Drying depends upon (Jayaramayan and Gupta, 2006): (a) Temperature, humidity and quantity of air used, (b) Size of the pieces being dried, (c) Physical structure and composition, (d) Airflow patterns within the drying system.

Heat is not the only factor which is necessary for drying. The condition, quality and amount of air being passed over and through the pieces to be dried determine the rate of drying. The amount of moisture contained in the air to be used for drying is important and is referred to as absolute humidity. The term relative humidity (RH) is more common and is the absolute humidity divided by the maximum amount of moisture that the air could hold when it is saturated. RH is expressed as a percentage and fully-saturated air would have an RH of 100% (Bidstrup and Day, 1994). This means that it cannot pick up any more moisture. Air containing a certain quantity of water at a low temperature will, when heated, have a greater capacity to hold more water. The table below gives an example of air at 29^{o}C with an RH of 90%. Such air, when heated to 50^{o}C will then have an RH of only 15%. This means that instead of only being able to hold only an extra 0.6 grams of water per kilogram (at 29^{o}C), it is able to hold 24 grams per kilogram. Its capacity to pick up moisture has been increased because it has been heated (Kudra and Mujumdar, 2002). When placed in a current of heated air, food initially loses moisture from the surface. This is the constant rate period. As drying proceeds, moisture is then removed from inside the food material, starting near the outside. Moisture removal becomes more and more difficult as the moisture has to move further from deep inside the food to the surface. This is the falling-rate period. Eventually no more moisture can be removed and the food is in equilibrium with the drying air.

Workshop tool machines used in fabrication of solar tunnel dryer: Different types of tools and materials are used in the designing and fabrications of the advanced solar tunnel dryer are given the table 1.

Results and Discussion

Design Considerations of solar tunnel Dryer: The solar tunnel dryer was designed as a portable solar system for drying of various agricultural products at various sites being developed and fabricated in the farm machinery labs, SHIATS-DU, Allahabad. For the design of the solar tunnel dryer, it has many parts such as semi cylindrical tunnel, main frame, frame base, solar collector, dryer, trays, air inlet and outlet, wire mesh sheet and fan system.

Main frame: Main frame of the tunnel dryer is made of four mild steel rectangular rods which have dimension of 4×1.5 m. three mild steel rods of 1.5 m are placed in the main frame to provide support to the content tray and insulation tray.

Semi cylindrical tunnel: The semi-cylindrical tunnel shape is formed by using 6 numbers of mild steel rods having required length (five rods which are used for the curves are 2.35m and one rod is used for the support for the polythene is 4m). While making semicircular frame by bending these rods, sufficient diameter cylindrical tunnel is formed. The floor was prepared with aluminum.

Base of tunnel dryer: Base of the tunnel dryer is made seven 1m rectangular rods which provide support to the main frame and four rods of 2m and five rods of 1.5m are used to improve the strength of the supportive rode as shown in the figure 1.

Solar collector: For the design of solar collector, a thermacole sheet with the dimension of 2 m × 1.5 m × 0.025 m has fixed on the main frame and then an absorbable plate mounted on it. This black plate acts as a black body to absorb solar radiant energy and transforms incoming sunlight into heat. In the process, the heated air becomes relatively dry and is blown over the required product to be dried, where it takes up moisture. Incoming sunlight on this half of the device additionally help to evaporate humidity from the foods.

Dryer: In the design of the dryer section two removable aluminum netted tray of 1m long and 0.75m broad inserted in the main frame. The pieces of vegetables and fruits are spread on the tray from the outside of the dryer and then placed it in the dryer for the drying of it.

Inlet and Outlet: The main parts of the system for the hot air flow in the tunnel dryer are inlet and the outlet of the dryer. For the design of the inlet system, a 2.5 cm of gap has given to the inlet side

Table-1: Tools and materials used in the Fabrication

Machine/Tool name	Purpose
Stellram hard core drills machine	Hole/Cell making
Lathe machine	Threading/Cutting/Finishing/Cutting/ Shaping/Machining.
Grinding machine	Grinding/Cutting tool
Cutting blade	Cut flat bar
Manual Facing Lathe Machine	Making circular wheel
Round file	Smooth rough edges
Electric welding machine	Welding
Steel scale	Measurement of linear distance
Steel tape	Measurement of linear distance
Vernier calipers	Measurement of outer diameter and inner diameter
Centre punch	Hole Marking
Choke	Marking
Hammer	Used to strike an object
Chisel	Cutting
Scissors	Cutting sheet metal
Vice	Clamping or holding
Spanner	Tighting nut and bolt
Screw driver	Tighting screw
Hand grinder	Grinding metal sheet
Flat file	Smooth rough edges

Fig. 1: Advanced solar tunnel dryer

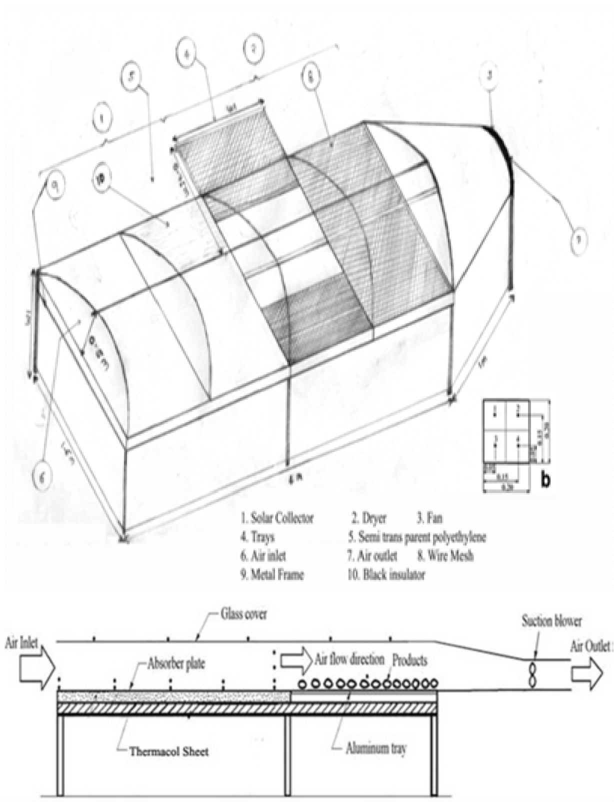

Fig. 2: CAD picture of solar tunnel dryer

of the tunnel dryer for the inflow of the natural air. Air sucked by the electric fan which was mounted on the exhaust hoper. The outlet system of the tunnel dryer is a 1.25 m long cylindrical hoper where a electric fan is mounted at one end which diameter is 0.35 m.

Fan system: By the fan system where a small electric fan is used, a reasonably stable temperature will be achieved within the system. This fan provide air stream to prevent the overheating of the drying product during high range of solar radiations. Since the PV-module provides maximum power in this case, the fans also run at maximum speed. When the solar radiations become weak, the module provides less power and the fan runs relatively slowly, whereby the air remained within the dryer for a longer time span. The schematic diagram of the portable solar tunnel dryer is shown in Fig. 1.

Design Parameters: The slope of the tunnel should be maintained by subtracting and adding 10° in the latitude of the site for summer and winter respectively. Since the site (Allahabad) has latitude equal to 81.2°C, so the same slope angle of the tunnel was selected, acceptable in both seasons.

Length and width of the dryer were decided keeping in view the easy portability at the desired locations. The height was selected to facilitate easy handling during loading and unloading of the products (Grabowski *et al.*, 2003). The function of collector section is to heat the air before entering into drying section. So a locally available and cheap black painted galvanized iron (GI) sheet (2 m × 1.5 m × 0.356 mm) is used for the collector and behaved like a perfect black body. A transparent polythene cover is used to transmit all the solar radiations through the cover. Moreover, the cover is used to minimize the conduction and convection heat losses to the atmosphere. The optimum area of the collector should be 40-45% of the dryer area to best utilize the available heat. Size of collector area was selected in such a way that all the heat energy carried by the air must be fully used for the drying of agricultural products placed in the tunnel dryer.

A low cost locally available thermocol was used to insulate the collector and drying unit. The insulation was held with bolts and silicon binding. The entire collector and dryer body were adequately insulated with 50 mm thickness thermocol insulation to minimize the losses of heat. The optimum air velocity (more than 1 m $s^{-1)}$ was used as suggested for STD (Hohenheim design). The volumetric flow rate (Q) is equal to the air velocity times the cross section of the dryer (Mason and Lorimer, 2002). The size of the PV panel was selected in accordance with the fan volumetric flow rate and velocity of air at the exit of STD. The purpose of PV operated DC fans is to increase and decrease the fan speed during high and low solar radiations respectively to maintain the optimum temperature within the dryer. The orientation of the dryer was maintained in East-West direction in order to achieve maximum solar radiations during the whole day. The tunnel slope was also designed to achieve maximum radiations perpendicular to the surface of the dryer in order to enhance the thermal efficiency of the solar dryer.

Performance evaluation of solar tunnel dryer: The overall drying efficiency is defined as the ratio of energy output of the dryer to the total energy input. Thus, overall efficiency of the system is given in Eq. (1) (Ekechukwu, 1999).

$$\eta = Qd / Qs \quad (1)$$

Where: Q_d is the heat energy available per unit time for drying in STD in kW, Q_s is the solar energy available per unit time at the collector section of STD in kW. Q_s is calculated by using Eq. (2) (Falade and Aworth, 2004).

$$Q_S = A_C I_t / 1000 \quad (2)$$

Where: *Ac* is the total collector area in m², *It* is the total solar radiations in W m^{-2}.

Collector efficiency is defined as the ratio of energy output from the collector area to solar energy input to the collector area. Solar energy input to the collector is computed using Eq. (3) (Ekechukwu, 1999).

$$Q_d = m C_p \Delta T \quad (3)$$

Where *Cp* is the specific heat of air in kJ $kg^{-1} K^{-1}$, ΔT is the change in temperature between collector exit and the ambient temperature in K; *m* is the mass flow rate of air in kg s^{-1} .

Heat gained through the dryer: The heat gained through the dryer was calculated without keeping any sample in the dryer (no load condition). For the performance evaluation, an anemometer was placed at the end of the collector section to measure the air velocity within STD. Due to unequal air distribution in any channel, a single point of measurement is not enough but grid was employed to record data at various points. Thermometers were used to record the dry bulb and wet bulb temperatures at ambient condition, collector exit and dryer exit sections.

Solar drying of different agricultural products: For experimental procedure and calculation, two points were selected to locate the psychometric processes within STD. Dry bulb and wet bulb temperatures were recorded at different time intervals during the drying process of the product. At the beginning of each experimental run, the initial moisture content of product was measured by oven drying method at a temperature of 105°C for 24 hours (Fellows, 1992).

Moisture removal rate: Moisture removal rate is calculated by using Eq. (4)

$$DR = m_a (H_2 - H_1) \quad (4)$$

Where H_1 and H_2 are the humidity ratios at the dryer section inlet and outlet respectively (kg of water/kg of dry air), *ma* was the mass flow rate of air in kg s^{-1}. The mass flow rate of air was calculated by using the Eq. (5)

$$Ma = \rho \times V \quad (5)$$

Where, ρ is the density of air in kg m^{-3}, *V* is the volumetric flow rate of the fan in m^3s^{-1}

Heating Capacity of STD: Capacity of STD for a mass flow rate of ma of dry air is given in Eq. (6)

$$Q = m_a (h_2 - h_1) \quad (6)$$

Where *Q* is the capacity of STD (kW), h_1 and h_2 are the enthalpies of air entering and leaving dryer section in kJ kg^{-1}

Psychometric analysis of product within the dryer: Psychrometric charts graphically represent the thermodynamic properties of air. For the psychometric analysis of the product inside the dryer, the dry bulb temperature and wet bulb temperature were measured from three different points of STD. These two measured values were used to locate a point on psychrometric chart. From this point, relative humidity, absolute humidity, specific volume, enthalpy and other physical and thermal parameters were determined. The intensity of solar radiation was recorded by the Pyranometer (SP Lite: response time < 1 s; Error = ± 5%).

This dryer is simple in construction and it can be constructed using locally available materials by the local craft man. The solar tunnel dryer was operated by a photovoltaic module independent of electric grid. The photovoltaic has the advantage that the temperature of drying air is automatically controlled by the solar radiation. The photovoltaic driven solar tunnel dryer must be optimized for efficient operation. Psychrometric chart can be successfully utilized for STD by plotting a process curve. The process curve can be used to evaluate the dyer performance during the dehydration process. The STD dried products are protected from dirt, insects and climatic conditions due to its perfect sealing. The air leaving the dryer was found to have still greater potential for drying more products. However, this should also be considered for other products, as this dryer is designed for multi-products use. The solar based renewable technology is free from operating cost and can play a vital role in promoting the field of post-harvest technology using solar energy.

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