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FORCED-CONVECTION INDIRECT SOLAR DRYER

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Abstract - *Here we present a model of a closed, indirect heating, forced convection solar dehydrator with desiccant which is economical, hygienic and works off the grid. This design benefits the people in rural areas of developing countries where electricity is unreliable or unavailable. This paper's contributions are as follows: First, an outline of the need of solar dehydrators is mentioned, basic theory, categories of solar dehydrators, and basic design criteria are given. Further, a model of a dehydrator is made which seeks to solve most of the draw backs. Lastly, an overview of future scope in this area is highlighted.*

***Key Words*: Solar Dehydrator, Food preservation, Forced Convection, Indirect Heating, Desiccant, Off-grid.**

1.INTRODUCTION

The world population is predicted to reach 9.7 billion by the year 2050 (UN June, 2019), further adding to global food security concerns. This increase shows 26% more human mouths to feed, with the highest demand growth in the underdeveloped areas of the world. Food supplies would need to increase by 60% (estimated at 2005 food production levels) in order to meet the food demand in 2050 [1]. So, the reduction of post-harvest food losses is a critical component of ensuring global food security in the future.

One of the earliest methods of preservation of food is by drying them. Some of the conventional drying processes range from natural sun drying and domestic dehydrators to industrial drying systems. In most of the developing countries, the use of fossil fuel dryers for agricultural produce has not been practically feasible due to its unaffordable costs to many farmers [2]. Open sun-drying has been effectively used since millennia. In this method, drying cannot be controlled and relatively inferior quality product is obtained. Drying rate is very slow and takes 7-14 days, depending on the weather conditions. Product can become contaminated with dirt, dust, rainfall, birds, animals, rodents, insects and microorganisms. It can be lost due to rains and winds; the texture can be deteriorated due to uneven drying. Under such conditions, losses can be as high as 30–60% of total quantity.

Most of these drawbacks can be countered by using a solar dryer of closed design. Drying or dehydration is the process of removing excess water content from any product in order to reach its standard moisture content. It is one of the important procedure of preserving agricultural product which has very high percentage of water content (about 65-75 %). Drying of food can be achieved chemically by using chemical desiccants or by chemical decomposition of the water in the substance and it can be done physically by increasing ventilation, temperature or other physical quantity. It can also be achieved mechanically by compression, centrifugal forces or gravity.

Thermal drying is generally used for drying agricultural products. It is the process of vaporisation of total moisture within the product by heat and its subsequent evaporation from the product. Thus, thermal drying is a synchronised heat and mass transfer process. The sensible heat of the air is reduced as it is used for moisture evaporation. Depending on the product, moisture transfer from inside the product to the surface is as liquid or vapour, but on the surface, it is a vapour only. Drying agricultural products increases their storage life, minimises losses during storage, and saves shipping costs. Drying is an important post handling process for agricultural produce. It increases the shelf life of the harvested product, improves quality and reduces post-harvest losses and lowers transportation costs since most of the water are taken out from the product during the drying process.

1.1 Basic Theory

Removal of moisture or drying is a complicated heat and mass transfer process which involves many variables such as relative humidity, temperature, vapour pressure within the product and vapour pressure in the surrounding atmosphere, convection coefficient, air flow, property of the product such as nature (hygroscopic or non-hygroscopic), size of particles, distribution on the drying surface and moisture content.

Moisture Content

It is defined as the amount of water (both bound as well as unbound) present in the product. The amount of moisture present in a material can be expressed either on the wet basis or dry basis and expressed either as a percentage or decimal. In this paper, wet basis moisture content will be used.

Wet basis:

The moisture content on wet basis is the weight of moisture present in the product per unit total weight of the material. The moisture content on wet basis is represented as,

$$M_{wb} = \frac{W_w}{W_t} \times 100$$

Dry basis:

The moisture content on dry basis is the weight of moisture present in the product per unit weight of the dry matter present in the product. The moisture content on dry basis is represented as,

$$M_{db} = \frac{W_w}{W_d} \times 100$$

Equilibrium Moisture Content

At a particular temperature and moisture content agricultural product has a characteristic water vapour pressure which affects the absorption or desorption of moisture to the environment.

Thus, there exists an equilibrium moisture content of any hygroscopic agricultural product after it has been open to a particular environment for long period of time. At this condition, the vapour pressure applied by the moisture held within the product equals the vapour pressure of the environmental air. This shows an equilibrium condition in which the rate of moisture desorption by the product to the environment equal to the rate of moisture absorption from the environment. Equilibrium moisture content is affected by several properties such as variety, water activity, maturity and crop chemical composition. The crops with a higher oil content tend to absorb less moisture from the environment than starchy crops.

Drying

During the drying of product, the latent heat of vapourisation of water in the grains is exchanged for the sensible heat of the grains of food and the drying air. This causes the grains and the air to cool just as the wet bulb thermometer in a psychrometer is cooled below the temperature of the dry bulb thermometer. These changes in the temperature and humidity of the air are represented on the psychrometric chart by a line parallel to the wet bulb lines.

Agricultural products always differ from other products due to their hygroscopic nature, the products like cement, sand, textiles, are non-hygroscopic in nature so the moisture held within them is only "unbound" moisture. The non-hygroscopic materials can be dried up to zero moisture content only due to their "unbound" moisture, however for agricultural products, there is always residual moisture remaining in the capillaries, the water component of juices or the water held by surface forces. It may also be unbound water held within the material by the surface tension of the water itself. [3]

The rate of moisture flow is only approximately proportional to the vapour pressure difference between the product and environment because of the crops resistance to moisture flow. When the product is heated at a constant moisture content, its vapour pressure increases and this causes moisture movement to its environment which is at a lower vapour pressure. There are two main drying rates for agricultural produce, namely constant rate drying period and falling rate drying period. [3]

Constant rate drying period:

In the constant rate drying period drying takes place from product surface and it is evaporation of moisture from free water surface. During this period, the surface of product is saturated with moisture and its temperature equally constant and almost equal to the wet bulb temperature of environment. The rate of drying during this period is mainly reliant on the environmental conditions and is slightly affected by the product quality. The end of the constant drying rate period is a noticeable decrease in the rate of moisture movement from inside the product below that sufficient to refill the moisture being evaporated from the surface as shown in fig.1[4]. For non-hygroscopic materials, such as glass, sand, textiles, cement, etc. the drying takes place within the constant drying rate period.

Falling rate drying period:

"The critical moisture content of any hygroscopic product is the minimum moisture content at which the minimum rate of free moisture movement from inside the product to the surface is equal to the maximum rate of moisture evaporation from the surface" [4]. When the moisture content is below the critical moisture content, the falling rate drying period begins as shown in fig.1[4]. This drying system depends on two factors: the rate of the moisture diffusing from the inside of the product to the surface and secondly on the rate of the moisture removal from the surface. This condition is subdivided into two phases:

1)The first stage involves unsaturated surface drying

2)Second stage is when the rate of diffusion of internal moisture to the surface is slow, this becomes the main factor in second stage

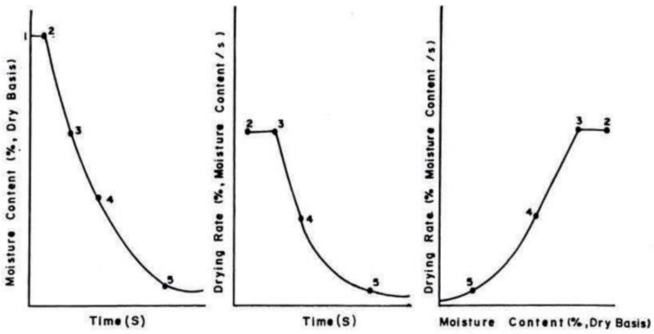

Figure 1: a, b, c.

The stage of drying for different agricultural products and food types is dependent on the initial moisture content of the product. Grains generally have an initial moisture content below critical moisture content so the drying takes place in the falling rate drying period. However, for products like fruits, vegetables and tropical crops, the initial moisture content is always more than the critical moisture content so the drying takes place in both the stages. Thus, the external and internal factors regulate the drying processes in the two-rate system and are important in finding the overall drying rate of products.

Latent heat of vaporisation:

The amount of energy absorbed by the product to vaporize water content present in the product. Basically, it is absorbed from environmental air because the moisture flows from product to the environment. Generally, it depends on the product condition, its moisture content and temperature of the environment. The higher the moisture content (of the product) and temperature, the lower is the heat of vaporisation. [4]

Safe storage time:

This is the period in which product is exposed to a particular environment at a particular moisture content. Above that content crop deterioration may occur and below that content the crop may be reduced. Hence to keep losses low the products must be dried to only the safe storage moisture content within safe storage time.

1.2 Types of solar dryers

Many studies have been done in the tropics and subtropics to develop solar dryers for agricultural products. Generally, there are four types of solar dryers, direct solar dryers, indirect solar dryers, mixed-mode dryers, and hybrid solar dryers [5]. Fig. 2 shows the classification of solar dryers [6].

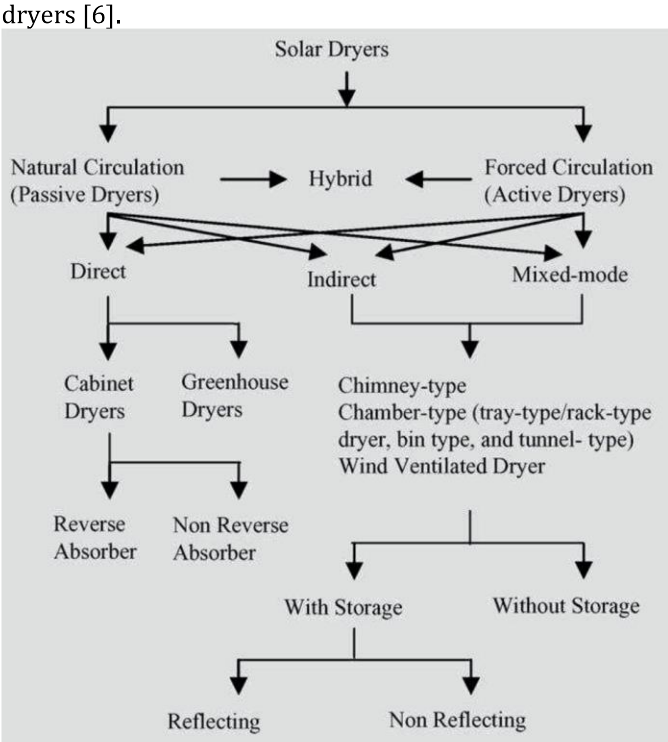

Figure 2: Classification of solar dryers

Indirect type solar dehydrator

It is the method recognized to overcome the demerits of direct solar drying as well as open sun drying. The working principle of indirect solar drying is as shown in fig. 3 [7], it varies from direct solar drying by not only heat transfer but also vapour removal. The drying products in these indirect solar dryers are placed on wire mesh trays for passage of heated air inside a cabinet and a long solar collector is used for collecting solar energy and continuous heating of the entering air into the cabinet. This completely heated air is allowed to pass through the product on the mesh which increases the temperature for moisture evaporation by convective heat transfer between the hot air and the moist product.

The drying takes place due to the moisture content gradient between the heated air and the air at the surrounding of product surface. With the entire process of collection of solar radiations, heating of air and passing it through drying material the product temperature rises and the moisture is removed through an exhaust provided at the top of the drying cabinet. We have chosen an indirect type solar dehydrator with a forced convection air flow.

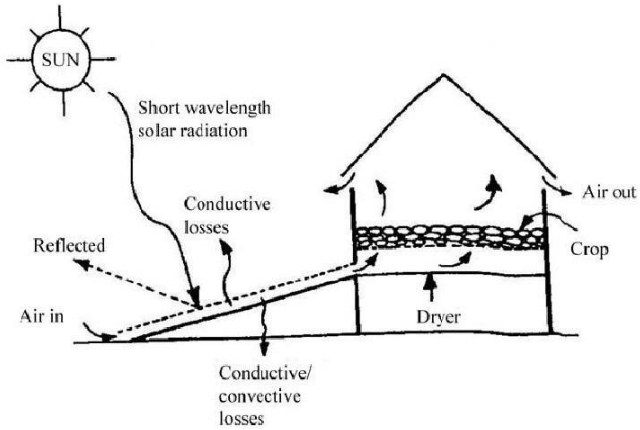

Figure 3: Working principle of indirect solar dryer

2. DESIGN AND FABRICATION

Energy balance

Let m_w denote the mass of water evaporated from a given quantity of rice and then absorbed by a mass m_a of drying air; let L denote the specific latent heat of vaporization of the water from the grain; let c_p denote the specific heat capacity of the air at constant pressure; and let T_i and T_f denote the initial and final temperatures of the drying air respectively. Then, the basic energy balance equation of the drying process is

$$m_w L = m_a c_p (T_i - T_f) \quad -(1)$$

Quantity of air required

The quantity of air needed for drying by means of a certain process may be estimated from a psychrometric chart, or from the energy balance equation. Consider as an example the amount of air needed to dry 1 kg of wet rice from an initial moisture content of 22% wet basis to the final moisture content of 14%. Assume that the ambient air has a temperature 30°C and a relative humidity 80%, and that it is heated to 45°C before being used for drying. The amount of water to be extracted from 1 kg of rice calculated is calculated as quantity Mw from the initial moisture content Ms of the rice and the desired final moisture content M_f with the help of equation Mw = $W_i \frac{(M_i - M_f)}{(100 - M_f)}$ where Wi is initial weight of rice. Mw in this example is 0.093 kg. We have mw = 0.093 kg, L = 2.8 MJ/kg, and C_p ~ 1.02 kJ/kg°C. Next, assuming T_i =45°C and taking a mean value of 32°C for T_f we obtain from equation (1) M_a = 19.6 kg. The corresponding volume of air calculated from equation PV = mRT is 17.3 m^3.

Flow of air required

Flow rate of air can be calculated by assuming the expected time in which drying must be completed T and the volume of air as calculated above V and Flow Rate Q=$\frac{V}{t}$. Suppose that we expect the drying to be complete in 30 hours which might be achieved through solar drying for 3 days with 10 hours of drying per day, or 4 days with 7.5 hours of drying per day (We cannot expect any drying to occur at night). The air flow rate should therefore be 0.094 m3/min. The volume of a 1 kg rice bed is calculated from the bulk density of rough rice. For approximate calculations it can be assumed to be 600 kg/m3. The volume of 1 kg of rice is therefore 0.017 m3. Combining the results, we obtain a required flow of 5.7 m^3/min per m^3 of grain or 5.7 complete air changes in the bed per minute.

Area of the solar heater/collector

In order to determine the area A of the air heater required to collect sufficient solar energy to dry the product, we must know the mass m of water to be evaporated from the mass of the product, the specific latent heat L of vaporization of this water, the quantity Q of global solar radiation falling on unit horizontal area per day, and the efficiency e of the solar collector.

Based on the preliminary design calculation, a cad model was made which shows the basic working principle. The corrugates aluminium sheet was the solar collector and was painted flat black to absorb the most radiation. A desiccant bed was added so that drying continues even at night time. When desiccant is overloaded by moisture in the night time, it is later dried automatically by the hot air when the sunlight is available again. Material and quantities were chosen as shown in the table 1.

Fabrication

Basic workshop tools such as table saw, drill machine, file, hammer, spray gun, hacksaw etc. were used in the fabrication process of the dehydrator. The wiring of the electric components was done as per the instructions of each manufacturer. The controls were mounted on an aluminium plate in front as shown in the fig. 4 [8] under the drying cabinet. This also houses the battery and other electronic components to keep the away from the effects of the environment.

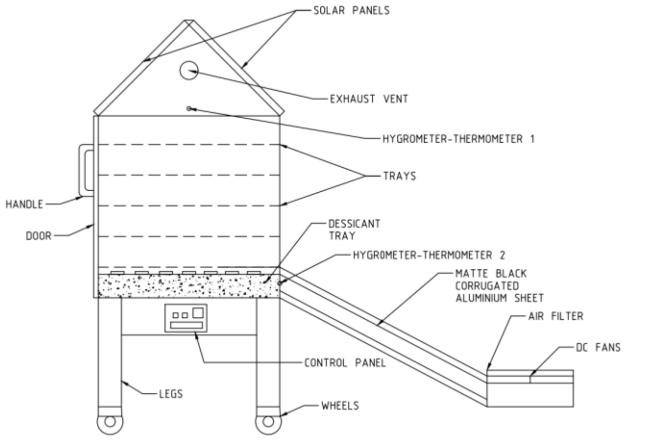

Figure 4: Working diagram of indirect forced convection dryer with desiccant

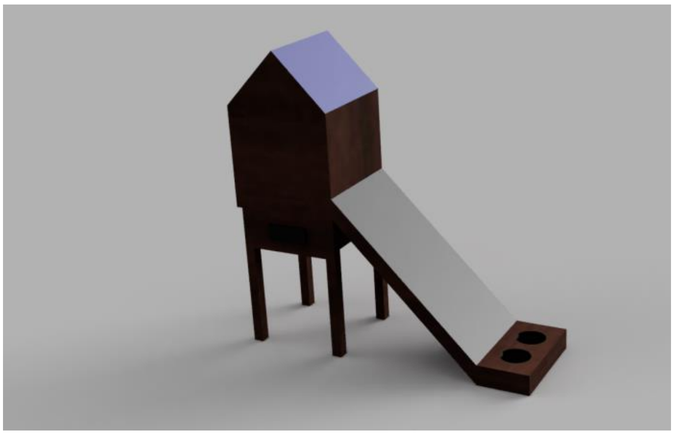

Figure 5: Rendered 3D model

Table -1: Bill of materials.

Sr. No.	Part Name	Quantity
1.	Solar Panel	20 watts
2.	Toughened glass	3.5' x 2' feet
3.	Battery charge controller (LM2596)	1
4.	SLA Battery	1 (7Ah)

5.	Two pole electrical wire	10m
6.	DC Fan 12v	3-Nos
7.	Hygrometer-thermometer	2-Nos
8.	Switches	2-Nos
9.	Commercial plywood (8x4 feet)	1
10.	Nails, screws, hinges, handles, glue, sandpaper, cloth	-
11.	Aluminium corrugated sheets	1sq.m
12.	Flat black paint 400ml	4-Nos
13.	Fan speed controller 1.8V – 12V/2A DC Motor PWM	1
14.	Desiccant (Silica Gel)	1 kg

3. RESULTS

Testing of Air flow

After 10 mins in the sun at 12 noon, the output of the thermometer at the output of collector yielded air at temperature of around 50 degrees Celsius. This is without any external air pressure (passive). Passive airflow temperature after 30 mins. was 52 degrees Celsius and airflow at 40cm3/sec.

Testing the battery charging system.

We have used a 12v 7.2 Ah SLA battery in conjunction with a 20watt solar panel. The solar panel provides around 22v at peak solar radiation which is then stepped down to 13.5 volts constant voltage to the battery by a buck boost converter of sufficient load capacity as per the solar panel. The fluctuating solar voltage is made constant to the battery and the fans run properly without reducing the battery voltage. This system makes it totally passive

Testing rate of dehydration.

When in peak sunlight, all 3 fans blow air through the sheet at a controlled speed which causes forced convection and allows hot air to pass into the cabinet. The heated air then passes through the mesh trays and through the food products. This causes dehydration as explained. In our testing, 500g of grapes spread across all the trays took 38 hours to transform into raisins. 1kg chopped tomatoes took 29 hours to dry. 1 kg Onion took 26 hours. Therefore, it can be assumed that any food material can take max of 3 days to fully dry if it is spread across evenly and finely chopped and solar conditions are acceptable.

Testing air characteristics at inlet and outlet.

Two hygrometer-thermometers were kept at the inlet of collector and outlet of the chamber, the results are shown in the table 2.

Table 2: Air Characteristics

Position	Temperature	Humidity
[1] Inlet	32 degrees C	44 RH
[2] Outlet	56 degrees C	88 RH

4. FUTURE SCOPE

As the population of humans are increasing, the need for food is more than ever. The future scope of solar dehydrator is mostly to increase usability for small scale farmers and users by decreasing costs, increasing reliability, versatility and making it easier to obtain. As these methods grow commonplace in developing countries, the resulting ease with which farmers can produce their own preserved grains, dried spices and vegetable powders and their decreased losses associated with traditional methods will increase their income. This in turn will increase production and lower the crisis of food for the human population.

5. CONCLUSION

A simple indirect, forced convection solar dehydrator was made which can be set according to a variety of products to be dried. This can be useful to small scale farmers who cannot afford industrial size fossil fuel driers but needs to quickly and effectively preserve their produce. Being off grid and low maintenance, it is easy to use.

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