Design and Evaluation of Solar Powered Dryer System with Integrated Thermal Energy Storage

Abhilash K.S, Nisam Rahman A, Shijin Kumar P.S

Abstract**: *Drying of food products in open air under sun is the most common and easiest way of drying. However, it cannot assure the hygiene of the dried product because of the involvement of wind-borne dust, rain, insects, rodents and birds. This will affects the quality of the product and hence may have contrary economic effects on domestics and global markets. Some of the problems associated with open-air sun drying can be solved through the use of a cabinet type or indirect type solar dryer. The major drawback of all these types of conventional solar dryers is that they cannot be used in cloudy weather or during night time. By incorporating Thermal Energy Storage (TES) we can make use of the dryer throughout the day or at least during late evenings. Water is one of the best sensible TES medium within its operating range. Solar water heater is a device used to collect solar energy and heat up water without any electrical or fossil fuel aid. So the idea of this project is to incorporate solar dryer with solar water heater so that the dryer can be used even at late evenings or in cloudy weather, and also it can be used as water heater for hot water consumption.***

Keywords**: *Solar Energy, Thermal Energy Storage, Solar Dryer, Design and Fabrication.***

I. INTRODUCTION

Drying is an essential process in the preservation of agricultural products for preserving it for long time or even for years. Drying is the process of removing the moisture content from the products. The quality of drying is determined by what amount of moisture is removed and the hygiene of the product. The process of drying is practiced from very ancient days itself for preserving the food for the off season when the productivity is very low [9]. It is very common for grains, vegetables and for some fruits. In olden days open drying is the most common and in other words, it was the only technique for crop drying. This is done by spreading the products on a clean flat surface under sun. But this has got several disabilities such as, the process cannot assure the hygiene of the product, it won't work in cloudy weather and in night.

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So the time needed for drying will be so high, and also it will not be practical in rainy reason.

In these circumstances, due to the progress in science and technology, some better ways other than open drying has been introduced. They used fire for drying crops in off weather. As time goes, man tried to understand more about the process of drying and the found that food products, especially fruits and vegetables require hot air in the temperature range of 45–60°C for safe drying [3]. Drying under controlled conditions of temperature and humidity helps the agricultural food products to dry reasonably rapidly to save moisture content and to ensure a superior quality of the product [4]. In the process of drying, heat is necessary to evaporate moisture from the grain and a flow of air is needed to carry away the evaporated moisture. There are two basic mechanisms involved in the drying process; the migration of moisture from the interior of an individual grain to the surface, and the evaporation of moisture from the surface to the surrounding air [5].

Later, by the involvement of industrialization, man began to dry the product in bulk quantity industrially. Hot air for industrial drying is usually provided by burning fossil fuels, biomass or by some electrical aids. This kind of drying is more preferable for commercial purposes since it will gives a continuous dried output throughout the year without affected by the climatic conditions [6]. But, high cost of fossil fuels, gradual depletion of its reserve, and environmental impacts of their use has put severe constraints on their consumption [7].

Industrial drying offers quality drying whereas its high cost limits its use. Open-sun drying suffers from quality considerations though it enjoys cost benefits. A closed type solar dyer can work with zero running cost and can also give better quality product compared to open drying [8]. But both open and closed type can be used only during sunshine hours. Whereas, drying of many agricultural products (e.g. cereals, pulses, foods and vegetables) are performed at the steady and moderate temperature and continuously for few days. In such a case, the thermal storage is required with the dryer for continuous drying so that possibility of drying during partial clouds and/or in late evenings and night hours continuously and hence, the storage will increase the utility and reliability of the solar dryers [9].

Since solar radiation cannot be stored as such, energy conversion should be done and also based on this conversion suitable storage medium also should be found. Solar energy can be stored by thermal, electrical, chemical, and mechanical methods.

Thermal energy storage can be classified in to sensible heat storage and latent heat storage system. In sensible heat storage, thermal energy is stored by raising the temperature of a medium [10]. Water, being inexpensive, widely available and due to its high specific heat capacity, can be effectively used to store sensible heat. A solar water heater harvests solar energy and heats the water which stores in a tank for consumption. A properly insulated tank can hold the temperature until the next morning. That is, the stored water of a solar water heater itself is a thermal energy storage system [11]. So by integrating solar dryer with solar water heater, we can design a TES integrated solar dryer and the design concept is shown in Fig.1.

Fig.1. Design concept

The rest of this paper is organized as follows. Section II presents the design considerations of proposed system. Design of the proposed system is provided in Section III. In Section IV, fabrication processing is explained in detail. Experimental results are displayed in Section V. Finally, Section VI concludes this paper.

II. DESIGN CONSIDERATIONS

A. Cabin Temperature

Temperature inside the dryer is the main factor influencing the drying rate and the quality of the dried product. The minimum and maximum temperature for food drying is 30°C and 60°C. If the temperature goes above 60°C then the food item may get burned off and if it goes below 30°C then drying will not happens [12]. So a temperature range of 45 – 60 °C is considered as the optimum temperature for drying food items [4].

B. Air Gap

The main mechanisms behind drying are the movement of moisture from core to the exterior surface of the particle and the evaporation of the moisture from the surface to atmosphere. From previous studies [13], it is recommended that for cabinet type solar dryer an air gap of 25mm should be provided at the bottom of the dryer tray.

C. Glass Cover or Glazing

Glass cover thickness is an important parameter in any type of solar collector. Glass cover is the part which induces greenhouse effect and increase the temperature inside the box. In previous studies [14], optimum thickness of glass cover is found to be as 4-5 mm.

D. Dryer Trays

Air circulation is one of the main parameter that affects drying. By placing the products on the plate will reduce the air circulation below it, so a net tray is used to aid air circulation within the drying chamber.

E. Drying Cabin

In normal cases the drying cabin should not have a good thermal conductivity. But in our case, the cabin material should have a good thermal conductivity so that it can transfer heat from the TES medium to the chamber. Aluminum can be selected for the cabin material since it got good thermal conductivity of 237W/m.k and is also economical.

F. Storage Tank

For storing the hot water an insulated water tank is needed. In normal case, cylindrical storage tanks are used for better pressure distribution. But in this case, since dryer cabin is also need to attach with this storage tank, a cubic shape is selected. Even though rectangular prism shape is more suitable for attaching the drying cabin, total surface area to volume ratio is lesser for cubic shape which results in less convective losses.

III. PROPOSED DESIGN

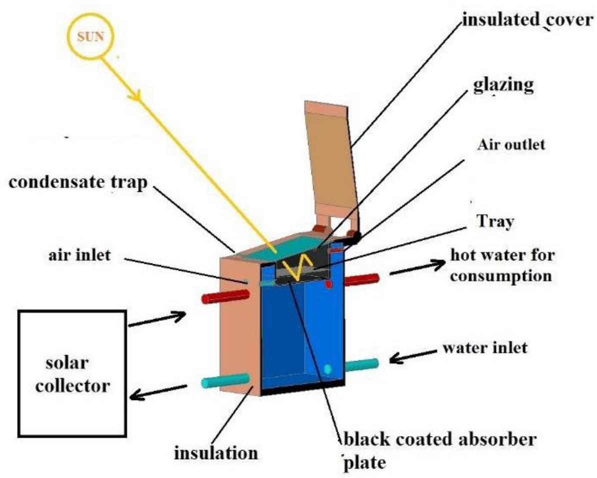

Fig.2. Basic Design

Fig.2 provides a clear idea about the proposed TES integrated solar dryer system. It is actually a combined solar water heater and dryer system which can be used for domestic purpose. The solar collector can be any type of the collectors such as flat plate, evacuated tube, etc. Improvement in storage is actually achieved by thermal stratification; that is, water of a high temperature than the overall mixing temperature can be extracted at the top of the container and water of a lower temperature than the mixing temperature can be drawn off from the bottom to make use even of short insulation periods and thus running the collector at a higher efficiency.

During sunshine hours, the glazing is exposed to sun so that the dryer can work as normal cabinet dryer. At the same time the solar collector will absorbs the solar radiation incident on it and heat up the water passing through it and stores in the tank, that is, water inside the tank is heated up with the same principle of solar water heater [15]. After sun set, by closing the insulated cover over the glazing, the whole tank and dryer unit will be in an insulated state except the heat escaped along with the moist air through the air vent.

Air vent is provided at bottom and top of the cabin so that fresh air can enter it below the tray and moist air can get out to the atmosphere. This will aid in the proper air circulation within the cabin which promote the drying process.

This will also help moist air to escape from the cabin so that condensation will not be occurred. Air vent size is a crucial parameter because, if the size increases, lot of heat will be loss to the atmosphere and if the size decreases, chance for condensation will increase. So optimized air vent will be selected by trial and error method. A condensate trap is also designed so that if in case of moist air in the cabin condense at the glazing, it can be drain off through it similar to what is happening in solar still [16].

A. Design of Cabin

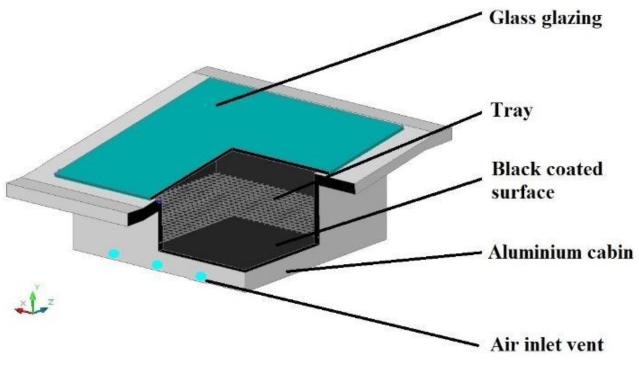

Fig.3. Design of cabin

The cabin material should have a good thermal conductivity so that it can transfer heat from the hot water to the chamber. Aluminium is selected for the cabin material since it got good thermal conductivity of 237W/m.k, economical, availability and also it is easy to fabricate. A flat edge is made at the top of the cabin so that the glass cover can easily rest on it and a rubber beading is kept in between the glass and the aluminium basin so that it will check the air leakage.

B. Design Specification

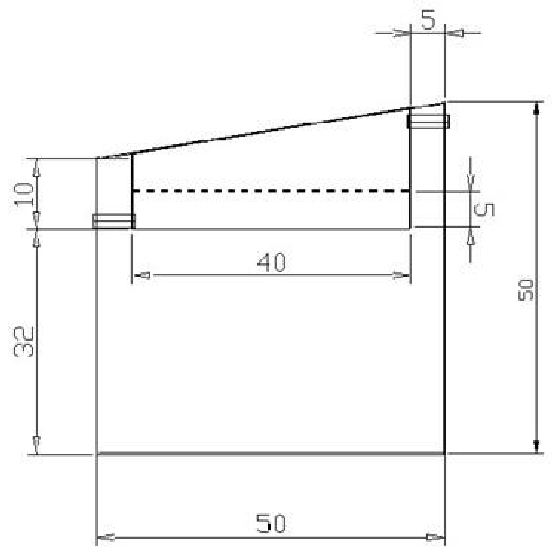

Fig.4. Drawing Side View

It is recommended that a constant exchange of air between atmosphere and drying chamber should be attained in solar food dryer design, thus the design of the drying chamber should be made as spacious as possible. On account with economic constraints and requirement, a cabin of base dimension of 40 x 40 cm^2 is selected. Selecting shape of tank as cubic since, total surface area to volume ratio is minimum for cubic shape on compared to rectangular prism [18]. Volume of the drying cabinet 22 L and volume of water tank is 94 L.

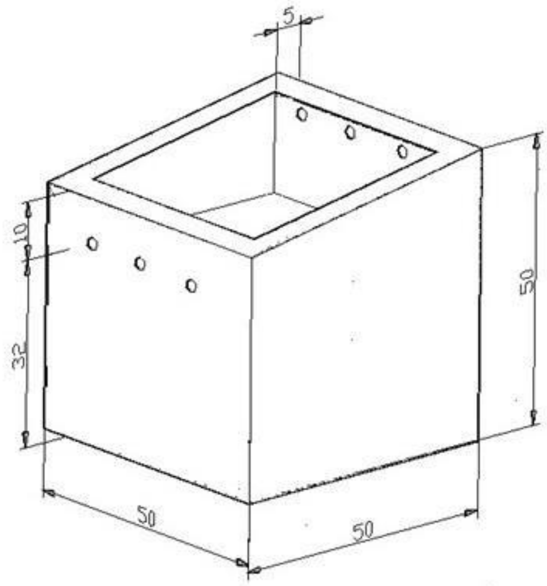

Fig.5. Drawing Isometric View

From a previous study of natural flow cabinet solar dryer, it is said that for a cabin volume of 783000 cm^3, an air inlet vent of 900 cm^2 is selected as optimum air vent size [17]. Since the shape, temperature range operating conditions of this particular work is similar to our method; the same ratio is used to find air vent size. And thus air vent size of 24cm^2 is selected. So five holes of 2.5 cm diameter is used for inlet and outlet air vent.

C. Fabrication

Cabin is fully made of aluminium sheet of 22 gauge. Actually sheet of lesser thickness is more suitable for this purpose because as thickness decreases, heat transfer rate increases. But as thickness deceases, its strength also decreases and so it may not withstand the water pressure since the whole cabin is partially immersed in the water.

Fig.6. Aluminium cabin

The cabin is made leak proof and inside surface is painted black. Metallic net of 1cm^2 having dimension of 39 x 39 cm^2 is used as tray in which the sample is placed for drying. The metallic net is also painted black so that to absorb maximum radiation. Transparent plain glass of dimension 45 x 45 x 0.4 cm^3 is used as the glazing. A beading is given on the cabin top so the glass can rest on it without leaving a gap between the cabin and the glass.

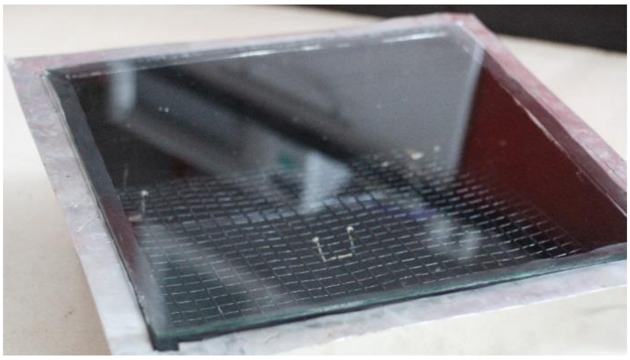

Fig.7. Black coated cabin with metal tray and glazing

Fig.8. GI Storage tank

Dryer cabin is fitted to the water tank and as per design. For withstanding high water pressure on the cabin, it is screwed on the water tank. Holes for inserting thermo couple, heating unit and thermostat were provided on the cabin edge. All the sharp edges are grinded and smoothened. The heating unit is then tested by filling water in the tank. Air vent holes are drilled through the tank and cabin walls. Pipes having same diameter of the vent and with a length to meet both walls are selected. These pipes were fitted on each holes and leak proof is done using Mseal. Then the model is painted for improving corrosion resistance.

Fig.9. TES integrated solar dryer

IV. EXPERIMENTAL RESULTS

Experimentation is done with different kind of samples such as little gourd, bitter gourd, green banana, potato, etc. in different conditions repeatedly for several days. Efficiency, drying rate (R), and percentage moisture content were calculated. For finding the optimized capacity, experimentation is done with different weight of samples. Experimentation is also done with simple cabin type dryer and also with open drying so that the new system can be compared with them.

$$R = \frac{\Delta W}{\Delta T} \quad (1)$$

where, ΔW is the weight loss during the time interval ΔT .

Normally, the moisture contents of grains, fruits and vegetables are usually measured on a wet basis, that is, the mass of moisture per unit mass of wet grain and written as X % (wb). If W_1 and W_2 are the weights of sample before and after drying (in grams), then percentage moisture content (M) is given by,

$$M = \frac{W_1 - W_2}{W_1} \quad (2)$$

For better understanding of the performance, efficiency also has to be calculated. For conventional cabinet type dryer, efficiency can be calculated by the following equation.

$$Efficiency = \frac{Weight\ of\ water\ evporated * Latent\ heat\ of\ water}{Total\ hourly\ solar\ insolation * area\ of\ collector} \quad (3)$$

For the currently TES integrated type dryer, the denominator of the above equation should be altered. Here the input energy is not only the solar radiation (input 1) that received directly on the collector but also the convective (input 2) and radiated (input 3) heat energy gained from the TES medium, i.e., from the water in the storage tank during night hours.

Input 1= *Total Hourly solar radiation * Area of collector*

Input 2 = $h\,A\,dT$

Input 3 = $A\varepsilon\sigma(T_s^4 - T_c^4)$

Therefore the efficiency of newly designed dryer can be calculated as,

$$Efficiency = \frac{Weight\ of\ water\ evporated * Latent\ heat\ of\ water}{Input1 + Input2 + Input3} \quad (4)$$

A. Experimentation on TES Integrated Solar Dryer

Experimentation is done for several days in the newly fabricated TES integrated solar dryer. Experimentation done on 750 grams of little gourd is shown below. The sample is sliced and spread in the dryer tray and is exposed to sun. Temperature inside the cabin, water temperature, solar radiation, and weight of the sample after drying were noted. Efficiency, drying rate and percentage moisture content where calculated for performance comparison [19]. After 24 hours of continuous drying, the weight of the sample has reduced to 143 grams. The product obtained is perfectly dried, clean and crispy. Within 24 hours, the moisture content on wet basis has attained a value of 80% with a drying rate of 25.3 grams per hour. And drying efficiency is found to be 39%.

Fig.10. Experimentation on TES integrated dryer

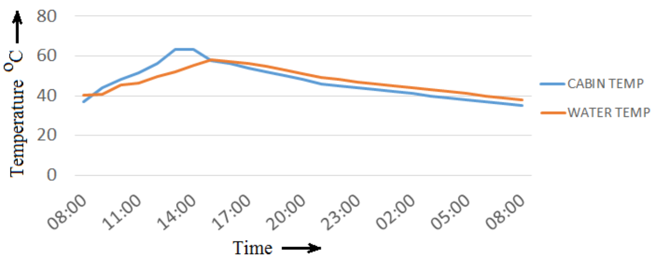

Fig.11.Variation of cabin and water temperature with time

B. Experimentation on Simple Cabinet Dryer

For comparing performance of newly designed dryer with conventional type, experimentation is done in simple cabinet type dryer also for few days. For experimentation 750 grams of bitter gourd is sliced and spread on the dryer tray and exposed to sun. At the end of day one the weight has reduced to 430 grams, and on second day it has further reduced to 245 grams. An efficiency of 20% was obtained on two days of drying. Percentage moisture content on wet basis has reached 65% with an overall drying rate of 25.5 grams per hour.

Fig.12. Experimentation on Simple Cabinet Dryer

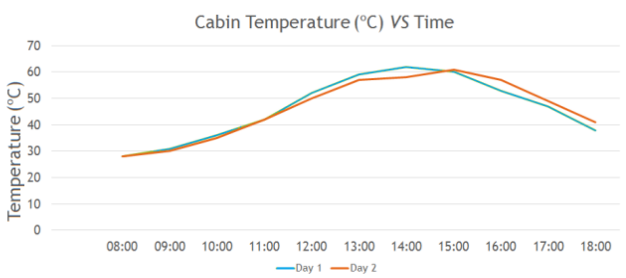

Fig.13. Variation in cabin temperature with time (simple cabinet dryer)

C. Experimentation on Open Drying

750grams of little gourd is sliced and spread on a clean surface and exposed to sun. At the end of day 1, the weight of sample has reduced to 380 grams and in next day the weight has reduced to 142 grams. At the end of 2nd day the moisture content on wet basis has reached a value of 78% with a drying rate of 30.4 grams per hour and an efficiency of 18.9%. Even though the rate of drying is better than that of cabinet dryer, the quality of product is comparatively less because of the presence of dust and dirt over the product. There is even noticeable color difference between cabin drying and open dried product.

D. Hourly Drying Rate

Weight of the sample has been measured after specific time interval for the whole day so that drying rate variation can be calculated which can be compared with conventional dryer.

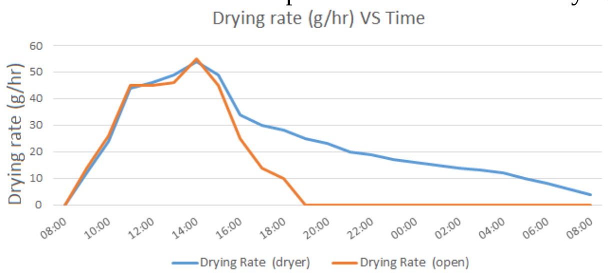

Fig. 14. Variation of drying rate with time

The variation of drying rate with solar insolation in conventional drying is very much higher than that in TES integrated solar dryer. It is clear that after sunset, drying rate is zero for the conventional dryer which means drying is not happening, but in TES integrated type, drying is happening even at late night.

E. Optimization of Dryer Capacity

For optimization of dryer capacity, experimentation is done with same kind of vegetables, in similar environmental conditions with different initial weights. The experiment is done with 500, 625, 750, 875 and 1000 grams of little gourd on both TES integrated solar dryer and also in conventional cabinet dryer. On noting the readings such as solar insolation, initial and final weights with each experiment, we can calculate the efficiency of the dryer. On plotting a graph we got a curve and by projecting optimum efficiency point of both curves to weight-axis, it can be seen that maximum efficiency is got on placing 750 grams of sample in it or in other words, efficiency decreases if the initial weight of sample goes below or above 750 grams.

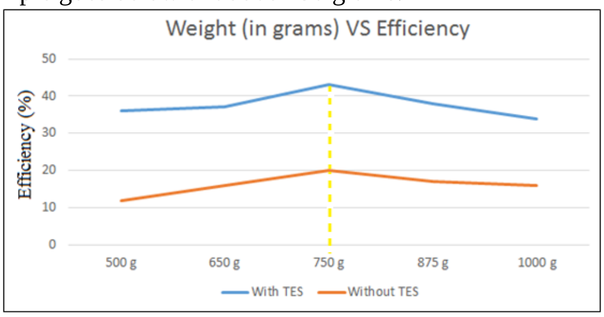

Fig.15. Variation in efficiency with initial weight

From the experimentations done on the newly improved dryer and conventional dryer, some comparisons are made to understand in detail about the performance enhancement attained. These compared results are explained below.

F. Drying Rate

Drying rate will give a clear idea about what amount of moisture is removed from the product in the time interval. On comparison, it is found that drying rate of open drying and that of TES integrated type dryer is almost same, but in cabin type dryer, it lags behind. For both open type and TES integrated type, the average drying rate is about 25 grams per hour which in peak times reaches almost 55-60 grams per hour. The reason behind the cabin drying lags behind open drying is that, in later one, air flow is not restricted, and natural wind may also promote drying. But in cabin drying, air flow is controlled.

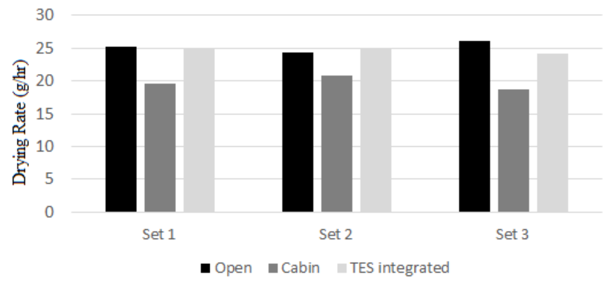

Fig.16. Drying rate comparison

G. Drying Efficiency

Drying efficiency is also an important parameter to compare and understand the performance of any dryer. Several experimentations are done on the newly developed dryer, open drying and with cabinet dryer in similar environmental conditions with same sample in same days. It is seen that open drying has the least efficiency, TES integrated dryer is much more efficient and cabinet type dryer comes in between. Even though drying rate is higher for open drying than of cabin type, efficiency comes vice versa, because area of collector is larger for open type than that of cabinet type. Maximum efficiency of cabinet dryer is only up to 20 percentage but that of TES integrated solar dryer is about 44 percentage which is more than twice. Which means the newly developed dryer is much better in performance in compared with other conventional solar drying techniques. The main reason for this much improvement is that TES integrated solar dryer needs only one day for drying while others need 2 days, so the total input solar energy is very high for both conventional cases.

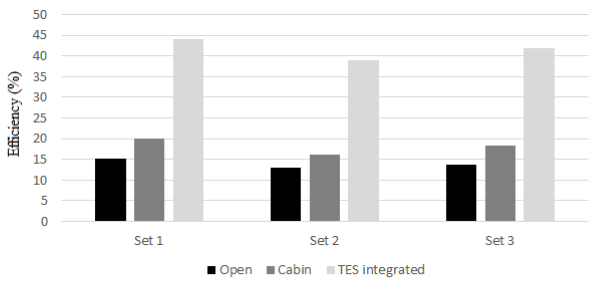

Fig.17. Efficiency comparison

H. Moisture Content (Wet Basis)

Percentage moisture content is the parameter which gives us an idea about how much moisture has escaped from the product. Even though there are wet basis and dry basis system for calculating moisture content, wet basis system only can be used in drying purpose. The experimentation is done for all three techniques for a whole day of 24 hour period and percentage moisture content is calculated. Here also cabinet type has the least outcome whereas open drying is always leading with 3% - 4%. But in the other hand, TES integrated type has the maximum percentage of about 82 percentage. This means that, within a one whole day newly developed dryer has made the product completely dried where the other two gives a partially dried product.

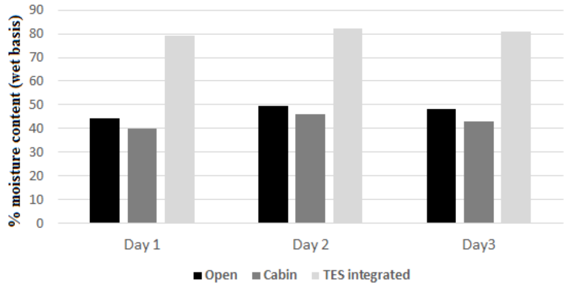

Fig.18. Moisture content comparison

Table 1Experimental Results

Metrics	Open Drying	Cabinet Dryer	TES Integrated Dryer
Drying rate (g/hr)	25.0	19.6	25.1
	24.3	20.8	24.9
	26.1	18.8	24.1
Efficiency (%)	15.2	16.2	39.1
	12.9	18.3	44.2
	13.8	20.1	42.6
Moisture content after a day (%)	44.3	43.1	82
	46.5	40.9	79
	48.4	46.2	81
No. of days required	2	2	1
Observation	Contaminated with dust, crispy, perfectly dried	Clean, Crispy, perfectly dried	Clean, Crispy, perfectly dried

V. CONCLUSION

Drying is an essential process in the preservation of agricultural products for preserving it for long time or even for years. Drying is the process of removing the moisture content from the products. Industrial drying offers quality drying whereas its high cost limits its use. Open-sun drying suffers from quality considerations though it enjoys cost advantage. A closed type solar dryer can gives a better quality output than open type but both open and closed type can be used only during sunshine hours. Whereas, drying of many agricultural products are performed at the steady and moderate temperature and continuously for few days. All these requirements can be fulfilled by using the newly developed TES integrated solar dryer. This type of dryer can dry any product at cloudy days or even at night which make it works continuously throughout the day. The variation of temperature in the drying cabin with the variation in solar insolation will be comparatively lesser for this kind of dryer. It doesn't need any running cost since the only input is solar radiation and since there isn't any moving parts the maintenance cost will be also negligible. Since it is a closed type dryer with controlled exposure to open air, the product obtained will be clean and edible.

So in other words, the newly developed TES integrated solar dryer is perfectly suitable for high quality incessant drying.

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