DESIGN AND DEVELOPMENT OF PROTOTYPE SOLAR DRYER USING THERMAL ENERGY STORAGE MATERIAL FOR DRYING FRUITS AND VEGETABLES CULTIVATED IN WESTERN MAHARASHTRA

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Abstract - *With food, shelter and clothing which are the basic need, energy is true need. Without energy nothing above mentioned is possible. With billions of population on the earth, food crises have taken place. Many people mostly in developing and under developing don't even get proper one time meal. There are many factors associating with the food insecurity. For conserving of the fruit and vegetables, we need to store them when they are in excess and use when needed. In this way we can reduce the demand and supply gap. But the storage and shelf life of fruits and vegetables is difficult. Due to moisture present in the fruits and vegetables they are prone to bacterial activity which in turn decays it. Also the cold storage around the world uses non renewable energy sources and thus the storing becomes costly. For all this drying of fruits and vegetables is necessary as the moisture gets evaporated and also its volume reduces which makes it enable to store for a more time. Drying is done by using non renewable energy sources but considering the fuels cost, pollution we are going to use solar energy for drying. From a large duration of time people are using sun drying for reducing the moisture but the problem lays in the contamination and irregular drying. For this reason we are going to use solar dryer which heats ambient air and uniformly distribute to the drying surfaces. Many designs are available like active or passive, direct, indirect and mixed/hybrid which improve the drying efficiency and reduce drying duration.*

***Key Words*: Dryer, Solar drying, Drying, Thermal Energy Storage, Food Security, Passive, Chimney, Solar Energy, Design, Efficiency, Perishable, Moisture.**

1. INTRODUCTION

Energy is one of the basic and fundamental need and right of human being. Energy used can be conventional or non-conventional. But due to growing population and industrialization there is large demand for energy. But due to scarcity of natural resources like coal, petrol etc there is big difference in supply of energy and actual demand. Due to large use of energy, there is problem of emission of harmful gases like CO_2, SO_2, etc which in turn cause global warming. Energy prices are also increasing due to demand and lesser availability. So clean energy like solar, hydro, wind are needed to use.

Sun radiates enormous amount of energy to the surrounding which can be used for various purposes. Solar energy is used for heating, drying and generating electricity. Drying is an important aspect in increasing the life of goods. Agriculture is one of the important occupations all over the world. The agriculture produce is perishable as it has large amount of moisture in it. Due to moisture the life of agriculture produce gets shorten as it can rot. So drying helps in decreasing moisture and increasing life stability of the product.

In conventional drying, the produce is kept under the sun directly. But there are some limitations as there are chances of contamination, rehydration, and degradation in quality due to uneven and uncontrolled drying. Also there are chances of damage by animals, birds and rodents in open drying.

We get major advantage if the drying is done in a closed cabinet as the temperature in it is maintained and it is free of any contamination. It doesn't require any excess energy during daytime and if required at night some additional provision can be done. The dryer can be designed in various types depending on the requirement and use. It can be direct type or indirect type, with use of collector or without collector or with the use of forced or natural convection. The results all across the world have shown that the produce has dried in less amount of time and the quality is good in solar dryer.

1.1 Solar Energy

Solar energy radiated from the sun in the form of radiation and light energy. It is a form of renewable energy which is inexhaustible. Solar energy used can be distinguished between active or passive upon the how it is captured and how it is converted. About 174PW of energy is received from sun every year of which 30% is reflected back. The solar radiation we get yearly is so vast that it is accountable for two times of the earth's non – renewable energy.

India is country situated in Northern Hemisphere at Tropical Region which gain large amount of solar radiation which is about 5-7 kWh/m^2, while have 275 sunny days. As India has high potential solar energy, it can be used for domestic purposes. The biggest problem is unreliability of the solar energy. India is an agricultural country with half the population relying on farming. Many a times the crops yielded are abundant and doesn't give good value of money. This also leads to rot of the vegetables or fruits maybe due to rodents or climate change which is an ultimate loss. To avoid this we need to remove the moisture from the vegetables and fruits for its better sustainability.

1.2 Drying of Fruits and Vegetables

Vegetables and fruits are perishable or short lived. They contain huge amount of moisture which can affect its shelf life. Due to moisture there can parasitic pollution which reduces life of fruits and vegetables. Drying removes the water content in fruits and vegetables and to increase their life and gain good quality. In solar drying the dried to be fruits or vegetables are kept in an enclosed box which may have forced or natural convection. Drying temperature is maintained and hence, the color and nutrients of vegetables or fruits remain intact. It takes less drying duration as the solar radiation is focused. The air is preheated in the collector which increases it temperature much more than that of ambient air. This also helps to keep dust, dirt; rodents away and thus increase the quality. The only disadvantage lays that it as investment at initial and capacity is restricted.

1.3 Solar Dryer

According air flow and heat, the solar dryer are classified. Solar dryer can be passive or active type depending on the convection type. Also it can be classified as mixed, direct or indirect. Many other factors are used for solar dryer like thermal energy storage, desiccant material or type of solar collector.

Solar dryer can be classified as Active or Passive Solar Dryer. In active type solar dryer, the flow of air is forced by means of blower and fan. Passive type of solar dryer the flow of air is by natural convection. Active Solar Dryer, the vegetables or fruits dry way lot faster than passive type. We get uniform drying in passive type of solar dryer. In active type of solar dryer for fan or blower we need electricity which can be costly and again will rely on non-renewable energy. Even if we use photovoltaic system for energy of fan and blower, the PV system is quite costly. So the passive type solar dryer is comparatively economical than active type.

In direct type the vegetables and fruits to be dried are directly kept under the transparent cover in drying chamber. In Direct Solar Dryer a box is made with a transparent cover of glass or plastic, provided with an inlet and outlet ports for air. Due to this the air is directly passed in the box and the drying temperature is not maintained due to which the drying is not uniform.

In indirect type solar dryer, the drying chamber is separate while the air is preheated in the collector which than transferred to the drying chamber. Due to this vegetables and fruits to be dried does not come directly in contact with sunlight. The only disadvantage in indirect type of drying is that for some fruits and vegetables we require direct sunlight as SAP pouches may heat up on upper side while bottom side may remain as it is.

Mixed Mode Solar Dryer is another type of solar dryer which comprises of indirect and direct type solar dryer. In this dryer, air is preheated in solar collector while drying chamber has a transparent which makes it enable to pass the direct sunlight due to which it has faster drying rate. There can be problem of SAP pouches case hardening. Also the drying takes place more quickly at upper side than at lower which makes drying non uniform.

1.4 Thermal Energy Storage Material

Thermal energy storage material can be classified in three types such as sensible heat storage (SHS), latent heat storage (LHS) and chemical heat storage (CHS). The energy system can be defined by the capacity which is the amount of energy which can be stored in the system; efficiency is the ration of charging and discharging.

Sensible heat storage has 10 – 15 kWh/t with efficiency of 50- 90% and cost is less. Sensible heat storage can be classified in sand, rock, concrete, water, octane, NaCl, cast iron, cast steel; aluminum, granite etc are the different types of sensible heat storage material.

Latent heat storage is thermal heat storage material which changes it physical state according to the charging and discharging. Due to energy density, volume reduces of latent heat storage. After charging or discharging the PCM changes from different phase like from liquid to gas or solid to liquid. Different types of PCM material are organic, inorganic and eutectic. Paraffin wax is harmless, low in cost, reliable, predictable but has low thermal conductivity.

Chemical heat storage uses endothermic and exothermic reactions for charging and discharging. Consider A is a chemical material which changes to C+D while charging and while changes back to A while discharging. In this reactions oxygen is evolved which is used further for other reasons. The only disadvantage is that not more study has done and some reactions can be toxic.

2. MATERIALS AND METHOD

For our design of solar dryer, we are using passive type solar dryer with no use of any external force of energy. For our design we are going to make use of chimney to create the buoyancy force so as to create natural convection and in course force the air to flow through the solar dryer. The parts of solar dryer are solar collector, drying chamber and chimney.

For our solar dryer we are going to design and construct a flat plate collector using simple mechanism. Solar collector is internally joined to the drying chamber so as to avoid the pressure drop. Drying Chamber is used to keep the trays which are used to keep the vegetables and fruits for dying. Drying Chamber is followed by the chimney which makes enables the flow of air.

In our experimental setup, we are going to fabricate the external structure with the help of mild steel with the help of welding. Later we are going to plaster the structure with plywood. In experimental design we have solar collector, thermal energy storage material, drying chamber and chimney.

Table -1: Solar Collector

Property	**Value**
Volume	1*0.50*0.1m
Wall thickness	0.012m bottom, 0.015m side
Space between glazing and absorber plate	0.04m
Medium of heat transfer	Air (1.293 kg/m^3)
Insulation thickness	0.04m
Inlet opening	3 square holes of 0.02m side
Outlet	Directly opened into the drying chamber
Collector orientation angle	30^o facing towards South
Emissivity of glass	0.88

Drying chamber is of 0.50m length, 0.35m height and 0.40m width with inlet for solar collector 0.50*0.10m is carved out. The outer supporting structure is made up of mild steel and plastered with plywood of 3mm.The drying chamber is wrapped with aluminum foil from inside so as to avoid moisture absorption by plywood also to reduce heat loss by radiation. At the exit of solar dryer, a divergent – convergent section is made at 15^o for the uniform flow of the air.

3. DESIGN CALCULATION

Data of study location

For installation of solar dryer we need to know the geographical information of the location. For more capture of solar radiation, a collector should be tilted such that to get optimum collector slope.

For designing of this project we are taking Sangli as a study location. It is a district in Maharashtra state in India. Following are the geographical details for the Sangli.

➢ Taking location as Sangli
  - Latitude: 16.8524^0 N
  - Longitude: 74.5815^0 E
  - Altitude: 550 m
  - Average Solar Radiation: 870W/m^2

Parameters considered for designing of solar dryer

Maximum amount of Vegetable or Fruits to be dried: 3 kg.

Using of thermal energy storage by using 30% of the heat produced by collector.

Reducing moisture to 20%

Maximum drying temperature in drying chamber considered at 60^0 C.

Considering minimum drying time= 9 hour.

Average Solar Radiation for Sangli = 870 W/m^2

Amount of moisture to be removed

Solar dryer is needed to remove the moisture content from the vegetables and fruits that are needed to be dried. For designing of the dryer, we need to determine the amount of moisture content that is needed to remove. We also need to set the maximum amount of weight that we need to dry.

W_i = Initial or maximum weight for drying is **3 kg**

M_i = Initial moisture content **90%**

M_f = Final moisture content **20%**

$M_w = W_i * (M_i - M_f)/ (100-M_f) = 2.625$ kg

Heat required to remove heat

For drying we need heat that we get from solar heat. Heat required to remove moisture from vegetable or fruits that we are going to dry.

$$Q_{req} = (M_w * L_w)/ t$$

Where,

Q_{req} = Amount of heat required to remove moisture (W)

M_w = Moisture needed to remove (kg)

L_w = Latent heat of vaporization (J/kg)

t = Minimum time for drying

Heat required to remove moisture content (Q_{req}) = 139.22 W

Minimum Area of Collector

$$Q_{req} = A_c * I_g * \eta_{optical}$$

Q_{req} = Amount of heat required (W)

A_c = Area of collector (m^2)

I_g = Solar radiation at the required location (W/m^2)

$\eta_{optical}$ = Optical efficiency of the glass used in solar collector

Area for solar collector = 0.50 m^2

Table -2: Specification of Drying Chamber

Parameter	Value
Volume Of Drying Chamber	0.50*0.40*0.35m
Outer Supporting Structure Material	Mild Steel
Walls Of Drying Chamber	Plywood Of 3mm With Inside Wrapped Aluminum Foil
Number Of Trays	2
Size Of Tray	0.48*0.40m
Distance Between The Trays	0.07m
Distance Of First Tray From Bottom From Outlet Of Solar Collector	0.07m

Chimney Design

Due to the difference of temperature created in chimney and ambient air, the air flows into the solar dryer. A convergent section is made of 15° at start of the chimney to give good air flow. As the design is based on passive type dryer, chimney's design is quite important. As due pressure difference between chimney and atmosphere air will flow across the drying chamber.

From literature survey it is found that pressure in chimney should be 0.5 mm of H_2O = 5 N/m^2

$$\Delta P_b = g\, H\, (\rho_a - \rho_{ch})$$

H = 1.6 m

Air velocity in drying chamber is considered as 1m/s

$$V = 0.453(D_g * \Delta T_{ch}/\rho)^{1/2}$$

D = 0.014m

Thermal Energy Storage Material

Paraffin Wax which is latent type thermal energy storage as it is economical and doesn't hamper with the quality in drying of fruits and vegetables. Its melting point is in the range and we can store it in small space.

Material used in Solar Dryer as Thermal Energy Storage = Paraffin Wax.

Assume 30% of energy used by PCM of total energy available.

$$Q_L = \int_{T_1}^{T_{cp}} m^* Cps\, dT + \text{heat of fusion} + \int_{T_{pc}}^{T_2} m^*Cpl\, dT$$

Amount of Paraffin Wax required = 5 kg

Table – 3: Specification of Thermal Energy Storage Material (Paraffin Wax)

Parameter	Value
Insulating material	Mineral wool
Fiber	Short fiber
Melting Temperature	700°C
Thermal Conductivity (λ)	0.038 W/mK
Density	50 kg/m³
PCM container	0.35*0.12*0.08m
PCM container material	Thick cardboard coated with aluminum foil
Inlet for PCM container	0.02*0.1m rectangle facing towards the solar collector
Outlet for PCM container	0.01m thick slits made at top of the container

Fig No. 1 : Side View of Solar Dryer

Fig No. 2 : Front View of Solar Dryer

4. EXPERIMENTATION

Temperature at different locations

For evaluation and checking out the performance of the solar dryer, we need to know temperature at different points in the solar dryer. The temperature is recorded at different points at solar dryer

Vegetables and Fruits for drying

The main objective of solar dryer is to dry the fruits and vegetables. Vegetables and fruits have a high moisture content due to which there are high chances that they will rot in fewer days. Many vegetables and fruits are seasonal, making them unavailable for rest of the year. Drying them or practically removing moisture helps to improve the life of vegetables and fruit.

No Load Test

For the performance of the solar dryer, we need to do a no load test. In no load test as the name suggest, the dryer is run and checked the performance without loading of any vegetables and fruits for drying. The no load test helps to find out the temperature across the solar dryer.

Load Test

Solar Dryer is loaded with vegetables or fruits for drying with different quantities and loaded in the dryer. Solar dryer is loaded with different quantities with maximum load which is 3kg. Also the drying performance is checked for the load less than maximum load. And the efficiency and moisture loss is calculated. It is checked if the moisture loss on wet basis is up to 20%.

4. RESULTS AND DISCCUSSIONS

Various readings are taken for different vegetables and fruits that are dried later along with their initial and final weights. Solar radiation and temperature are recorded at hourly basis. Trials were taken on no load, full load, and partial load with and without thermal energy storage material.

From No Load Test with and without PCM it can be seen that the temperature of dryer is more and comparatively constant for dryer when phase change material is used. The maximum temperature reached with the use of phase of change material is found out to be 68.7°C while when dryer is run without the temperature, it is found out to be 69.7°C. The temperature after sunset for dryer running with PCM is 37.5°C max and 26.6°C min, while for dryer when its running without PCM temperature is 36.5°C max and 21°C min. It can be seen that even though the maximum temperature is more when PCM is not used, it's drastically reduces after sun is down and becomes less than the ambient air temperature.

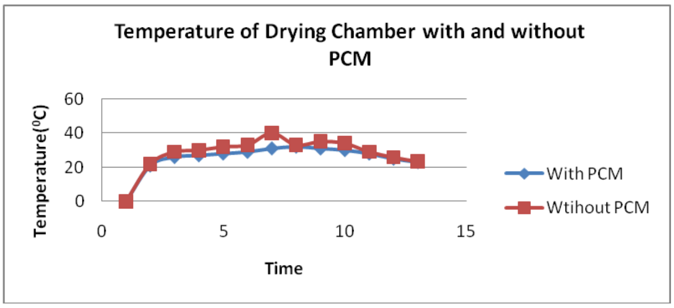

Chart No. 1: Temperature Vs Time with and without PCM

Trial taken with full load with use of thermal energy storage material. Following are the results of the trial.

Specimen to be dried = Sliced Tomatoes

Date of trial = 2/1/2021 and 3/1/2021

Weather = Sunny

Initial weight of Sliced Tomatoes on Tray 1 = 1.5 kg = 1500 g

Initial weight of Sliced Tomatoes on Tray 2 = 1.5 kg = 1500 g

Total initial weight of Sliced Tomatoes = 3 kg = 3000 g

Final weight of Sliced Tomatoes on Tray1 = 0.1318 kg = 131.8 g

Final weight of Sliced Tomatoes on Tray 2 = 0.153.4 kg = 153.4 g

Total final weight of Sliced Tomatoes = 0.2852 kg = 285.2 g

Average solar radiation = 591.75 W/m²

Latent heat of vaporization of water = 2357.6 kJ/kg

Total duration of drying = 16 hours

Moisture Loss

$M_L = W_i - W = 2.7148$ kg

Drying Rate

$D_R = dM/dt = 0.1696$ kg/hr

Loss of moisture on wet basis

$M_d = [(W_i - W_f)/ W_i] * 100 = 90.49$ %

System drying efficiency

$$\eta_d = \frac{[\text{Moisture Loss } M_L * \text{Latent heat of vaporization } L_w] * 100}{[\text{Area of Collector } A_c * \text{Average solar radiation } I_g * \text{time } t]}$$

$\eta_d = 37.55$ %

Collector Thermal Efficiency

$\eta_{coll\text{-}thermal} = Qu/(Ac * Ig) * 100$

$Q_u = m_a C_p (T_{oc} - T_a)$

$= 153.74$ W

$\eta_{coll\text{-}thermal} = 47.51$ %

When performing at full load of 3kg of sliced tomatoes with PCM, the duration of drying period is 16 hours. The maximum temperature at drying chamber is 60.5°C which is on safe side of drying. The weight of sliced tomatoes at the end of drying is 0.2582kg. Tomatoes get dry at initial drying time very quickly but later take time due to inbound water present in it. Due to use of TES the temperature in drying chamber remains more than ambient air even after 6pm.

The drying curve is plotted against the time and moisture content. It seen from the graph that at the initial stages when moisture is present on the surface the moisture is reduced at faster while after the drying becomes slow.

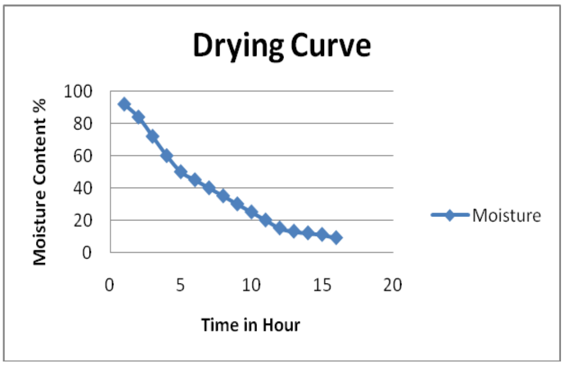

Chart No 2. : Drying Curve

Proximate Analysis of Fresh Sliced Tomatoes

The proximate analysis on fresh sliced tomatoes shows that moisture in the tomato is up to 92%, crude fiber is 1.19%, pH level is 4.57 while sugar content is 3.5 and proportion of carbohydrate is 2.50%.

Table - 4: Proximate Analysis of Fresh Sliced Tomatoes

Parameter	**Value**
Moisture (%)	9.03 ± 0.05
Total Soluble Solid (ºBrix)	-
Carbohydrate (%)	8.50 ± 0.86
Crude Fiber (%)	5.60 ± 1.05
pH	3.5 ± 0.5
Fat	0.2 ± 0.30
Ash	0.16 ± 0.40

Proximate Analysis of Dried Sliced Tomatoes

Parameter	**Value**
Moisture (%)	9.03 ± 0.05
Total Soluble Solid (ºBrix)	-
Carbohydrate (%)	8.50 ± 0.86
Crude Fiber (%)	5.60 ± 1.05
pH	3.5 ± 0.5
Fat	0.2 ± 0.30
Ash	0.16 ± 0.40

Table - 5: Proximate Analysis of Dried Tomatoes

Approximate analysis on fresh sliced tomatoes shows that moisture in the tomato is up to 9.03%, crude fiber is 5.60%, pH level is 3.5 while sugar content is negligible and proportion of carbohydrate is 8.50.

Fig No.3 : Sliced Fresh Tomatoes

Fig. No. 4 : Dried Sliced Tomatoes

Fig No. 5 : Tomatoes After Rehydration

5. CONCLUSIONS

From the studying the concepts of drying it is seen that drying is removal of moisture from the fruits or vegetables which increases its shelf life. Open drying is vastly used all over the world but it's not suitable due to uneven drying , dust and attacks by the rodents. Therefore, the drying should be carried out in temperature controlled and inside the box as it produces the good quality dried vegetables or fruits that are needed to be dried. There are different types of solar dryer designs are available.

Indirect type dryer is one of the good efficiency dryer with natural flow for uniform drying with its calculated efficiency up to 37%. Natural convection helps the air remain in the drying chamber for more duration and helps reducing drying time. Thermal energy storage used helps in the controlling the temperature in inside the drying chamber. Even after 6 pm when sun is down and ambient temperature is less, the temperature in the drying chamber tends to be constant. The temperature is even more in drying chamber at 8pm which is more than ambient air.

The limitation lays in the capacity of the solar dryer as it requires high energy and so the area of collector should large for generating the heat energy.

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