PERFORMANCE ANALYSIS OF A SOLAR GRAPE DRYER WITH THERMAL ENERGY STORAGE BY PCM

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Abstract - ***In the recent years there has been a growing interest in agricultural products dryer from the point of view of the commercial value for farmers and reduction in the wastage. This research includes the design and manufacturing of solar grape dryer. The use of solar energy in recent years had reached a remarkable edge. The continuous research for an alternative power source due to the perceived scarcity of fuel fossils is its driving force. It had become even more popular as the cost of fossil fuel continues to rise. Of all the renewable sources of energy available, solar energy is the most abundant one and is available in both direct as well as indirect forms. There has been a remarkable achievement in solar drying of grapes due to sustained research and development associated with the adoption of advanced technologies. Grape is one of the world's largest fruit crops. The world production of grapes is currently 73,516 million tones out of which India accounts for 1.2 million tones.***

Key Words: *solar dryer, grapes, PCM, performance*

1. INTRODUCTION

Preservation of fruits, vegetables, and food are essential for keeping them for a long time without further deterioration in the quality of the product. Several process technologies have been employed on an industrial scale to preserve food products; the major ones are canning, freezing, and dehydration. Farmers dry food products by natural sun drying, an advantage being that solar energy is available free of cost, but there are several disadvantages which are responsible for degradation and poor quality of the end product. Certain variety of food products are not supposed to be dried by natural sun drying because they lose certain basic desirable characteristics. Experiments carried out in various countries have clearly shown that solar dryers can be effectively used for drying agricultural produce. It is a question of adopting it and designing the right type of solar dryer. Drying involves the application of heat to vaporize moisture and some means of removing water vapor after its separation from the food products. It is thus a combined and simultaneous heat and mass transfer operation for which energy must be supplied. The removal of moisture prevents the growth and reproduction of microorganisms like bacteria, yeasts and molds causing decay and minimizes many of the moisture-mediated deteriorative reactions. It brings about substantial reduction in weight and volume, minimizing packing, storage, and transportation costs and enables storability of the product under ambient temperatures.

1. Solar Drying

Solar drying has been used since time immemorial to dry plants, seeds, fruits, meat, fish, wood, and other agricultural, forest products. In order to benefit from the free in recent years to develop solar drying mainly for preserving agricultural and forest products. However, for large-scale production the limitations of open-air drying are well known. Among these are high labour costs, large area requirement, and lack of ability to control the drying process, possible degradation due to biochemical or microbiological reactions, insect infestation, and so on. The drying time required for a given commodity can be quite long and result in post-harvest losses (more than 30%). Solar drying of agricultural products in enclosed structures by forced convection is an attractive way of reducing post-harvest losses and low quality of dried products associated with traditional open sun-drying methods [1]. In many rural locations in most developing countries, grid-connected electricity and supplies of other non-renewable sources of energy are unavailable, unreliable or, too expensive. In such conditions, solar dryers appear increasingly to be attractive as commercial propositions [2-3]. During the last decades, several developing countries have started to change their energy policies toward further reduction of petroleum import and to alter their energy use toward the utilization of renewable energies.

Solar radiation in the form of solar thermal energy is an alternative source of energy for drying especially to dry fruits, vegetables, agricultural grains and other kinds of material, such as wood. This procedure is especially applicable in the so-called "sunny belt" world-wide, i.e. in the regions where the intensity of solar radiation is high and sunshine duration is long. Both the ambient temperature and the solar radiation can vary much from one year to another, and the distribution of temperature and solar radiation vary during different years. In India, there exists significant potential for tapping solar energy due to more sunshine hours.

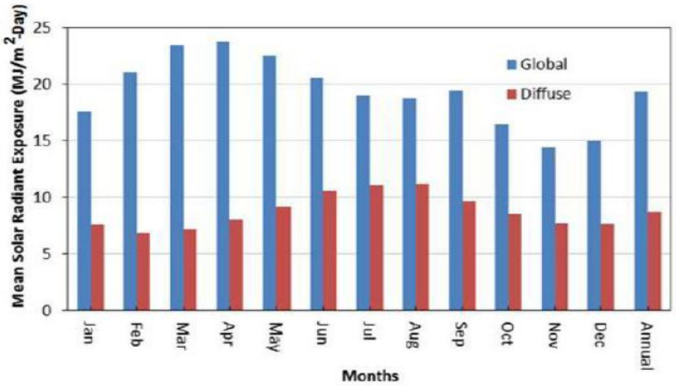


Chart - 1: Mean monthly solar radiant exposures (MJ/m^2 - Day) in Maharashtra, India (Source: MNRE, India)

2. PCM for Grape Drying

Drying is one of the most energy-intensive processes in agro-products industry. For this reason, using solar energy appears as an attractive not polluting alternative to be used in drying processes. However, the daily and seasonal fluctuations in the radiation level require using energy accumulators with phase change materials (paraffin wax), to have continuous drying processes. The dryer includes paraffin wax as phase change material. The input variables were ambient temperature and solar radiation, both not controllable. Optimizing the use of solar energy. The idea to use phase change materials (PCM) for the purpose of storing thermal energy is to make use of the latent heat of a phase change, usually between the solid and the liquid state. Since a phase change involves a large amount of latent energy at small temperature changes, PCMs are used for temperature stabilization and for storing heat with large energy densities in combination with rather small temperature changes.

Paraffin Wax

The successful usage of PCMs is on one hand a question of a high energy storage density, but on the other hand it is very important to be able to charge and discharge the energy storage with a thermal power, that is suitable for the desired application. One major drawback of latent thermal energy storage is the low thermal conductivity of the materials used as PCMs, which limits the power that can be extracted from the thermal energy storage. As one of the goals of latent energy storage is to achieve a high storage density in a relatively small volume, PCMs should have a high melting enthalpy [kJ/kg] and a high density [kg/m^3], i.e. a high volumetric melting enthalpy [kJ/m^3]. Paraffin has an excellent stability concerning the thermal cycling, i.e. a very high number of phase changes can be performed without a change of the material's characteristics. The selection of the PCM for grape drying systems depends on the operating temperature range of the HTF which in turn is based on the application. A variety of PCMs exist, the temperature obtained by the HTF in flat plate collectors, and the desirable PCM properties, are the decisive factors in selecting the PCM. The test facility was meant for an application that demands hot air in a medium temperature range in between 50^{0}C to 60 ^{0}C.

The need to maximize the efficiency of the solar system restrains the selection of high melting temperatures of the PCM though higher storage temperatures could be advantageous for several applications. In such cases, the maximum heat gain can be obtained from the solar system and the fraction of high temperature energy requirement can be made available from other sources. The commercial phase change material (PCM), HS 58, which has a melting temperature of 57-58^{o}C was chosen considering the above factors The disadvantages of the PCMs are their cost and degradation of properties when subjected to high thermal cycling at high temperatures in long term TES applications.

3. DESIGN & PROGRESS OF SOLAR GRAPE DRYER

Overall view of solar dryer (Side View*)*

The developed solar dryer consist of the different components like flat plate collector based solar air heater, thermal energy storage system, dryer cabinet and blower. On the basis of the criteria mentioned, the design of the individual component was prepared and corresponding parameter (i.e. relative dimensions and material for solar flat plate collector, dryer cabinet and PCM storage) were calculated. The procedure of design and calculations for each component is mentioned below. The overall project is designed for drying of 30 kg of grapes. Taking into consideration the drying area required for 25 kg of grapes the drying chamber is designed. Then from the calculations carried out the total energy required for drying is calculated based on the desired final and initial moisture content of grapes. Then the design of PCM storage was calculated for TES storage.

4.1 Design of drying chamber

The energy required to dry the grape is the function of the moisture content to be removed. So, the testing report of the wet (raw) grapes and the market purchased dried grapes were taken from the labs for moisture contents. The reports resulted in the initial and the final moisture as 80g/110g and 20g/100g respectively. Using this data obtained the energy calculations were done.
Considering amount of moisture content: 80% for wet grapes & 20% for dried grapes.
Amount of moisture to be removed from given quantity of grapes to be dried,

Amount of moisture = $\frac{mp(mi-mf)}{(100-mf)}$ = 18.75 *kg of water*

Here, m_p = mass of product
m_i= Initial moisture
m_f= Final moisture

Amount of heat required to evaporate water = $\mathbf{Q = m_w \times h_{fg}}$

$\mathbf{h_{fgw} = 4186\ (597\text{-}0.56 \times T_p)}$ = 2.35MJ/kg

Tp-initial temperature of the product
Amount of heat required to evaporate water = $\mathbf{Q = m_w \times h_{fg}}$= 44.06 MJ, Assume 10 % loss of heat in drying chamber.
Amount of heat required to be supply = 44.06× 1.1 = 48.46MJ ≈49MJ.Amount of heat required to be supply = 49MJ
Total energy to be supplied for drying of grapes = **49MJ.**

4.2 Thermal Energy Storage Calculations

The total heat energy to be supplied for the drying purpose will be the heat retracted from the thermal energy storage and supplied through the parabolic trough collector. But for knowing the exact proportionate of energy supplied from the either energy sources it is necessary to carry out the calculations of thermal energy storage initially. For the purpose of thermal energy storage Phase Change Material type is used. The material selected for PCM is paraffin wax.

Fig - 5: Thermal energy storage system

The PCM is stored in the aluminium pipes. Depending on the dimensions of the storage pipes the quantity of PCM stored is known. Further from the quantity of PCM stored the energy stored in it is calculated.
Properties of paraffin wax: (Paraffin 60)
Melting temperature: 56^0 C to 64^0C ≈ 60^0C
Boiling temperature: 370^0C
Latent heat of storage (Fusion heat) = 210 kJ/kg

Dimensions of Aluminium Pipe:
Outer diameter (D) = 51 *mm*
Inner diameter (d) = 45 *mm*
Length of Pipe (L) = 1*m*
Calculation for TES using PCM
Total volume of Aluminum pipe = $\pi/4 \times d^2 \times L$ = $1.59\times 10^{-3} m^3$
Amount of PCM stored in single pipe = $m = \rho \times V$ = 1.43*kg*
Total number of pipes= 10
Total PCM stored = 1.43×10= 14.3*kg*
Amount of energy stored in per kg of PCM = 210 *kJ/kg*
Amount of energy stored in given PCM = 210 *kJ/kg*× 14.3*kg* = 3003*kJ* = 3.003*MJ*
Considering efficiency of Thermal Energy Storage System = 80 %
Actual energy retracted from PCM = 3.003× 0.8 = 2.4*MJ*
Determination of total collector area required
The total energy required for drying purpose is 49*MJ*. From PCM 2.4MJ of energy is retracted. The remaining energy is to be supplied from the Flat Plate collector. So the energy to be supplied by collector = 49-(2.4×Number of days we are using TES System)
Here, the drying time is 35 hr, so TES system is used for 5 days

= 49 - 2.4×5
=37MJ

4.3 Total collector Area required

Assuming the efficiency of collector (η) = 30%

(Generally efficiency of flat plate collector is 28-25%.But by Using Reflector Surfaces the Flat Plate Collector Efficiency can be enhanced up to 30%)

Fig - 6: Construction of flat plate collector

Intensity of radiation (I) = 800 W/m^2
According to Solar Radiation Hand Book data by Solar Energy Centre, MNRE Indian Metrological Department it gives the $25.12 MJm^{-2}$ per day.
Assuming area of flat plate collector to be $0.8m^2$
Energy retracted from FPC = η×25.12×Area
=7.455MJ per Day
Total Energy supplied from FPC =7.455×5 = 37.25 MJ
The Flat Plate collector area required for supplying the essential heat energy is $0.8m^2$.

5 Performance of developed solar grape dryer

This chapter gives test methodology to analyze the performance of developed solar grape dryer with thermal energy storage by PCM. Accordingly the parameters needed to analyze the performance are recorded as per test methodology. The sample observation table is also given. The measuring instruments used to measure the said parameters are described with specifications. Test methodology has been planned and executed in order to achieve stated objectives. The experiment was performed on the developed solar dryer with following test methodology.

Test methodology have been planned and executed in order to find the drying time with and without incorporation of thermal energy storage in developed solar dryer. The effect of mass flow rate of air on moisture content, moisture loss, drying rate, drying time and dryer efficiency has to be evaluated and accordingly test have been executed.

- As pretreatment of grape remarkably affect on drying time hence it is decided to complete whole experimentation with pretreatment of grape by dipping it in to calcium carbide and dipping oil (olive oil) for three minutes.
- Experimentation has been carried out for drying of grape from initial moisture content of 80 % to final moisture content up to 20% with and without incorporation of thermal energy storage system for variable mass flow rate of air.
- Mass flow rate of air kept for the individual set of experimentation as 0.01484, 0.01569, 0.01650 and 0.01729 kg/sec though dryer cabinet and
- With selected mass flow rate of air , time to time reduction in weight of the sample grape , flat plate collector air inlet, outlet temperature, dryer cabinet exit temperature ,intensity of solar radiation are noted till final moisture content reduced to 20 %.
- With incorporation of TES, inlet and outlet temperatures of air passing through the thermal storage system have also been recorded, additionally with the parameters mentioned above.

6 Results and Discussion

The results obtained from the experimentations carried out on the solar dryer by the mentioned testing methodology are presented in the following section. Various graphs are plotted for the study of variation of moisture with respect to time, variation of intensity of solar radiation, study of effect of mass flow rate on drying time, variation in the efficiency of Flat Plate Collector etc.

6.1 Variation of Intensity of solar radiation with time

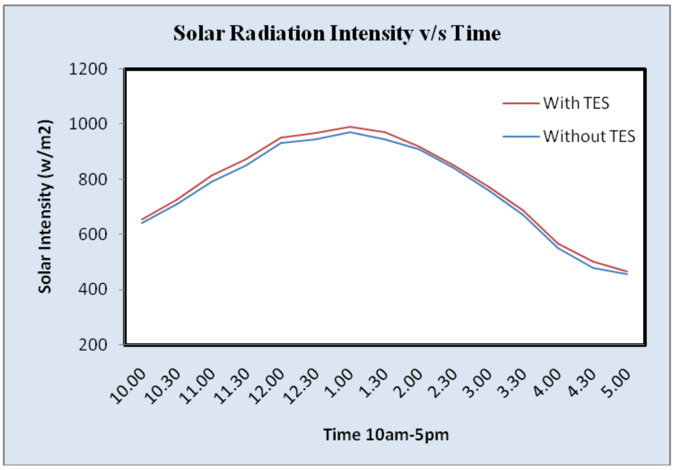
The variation of solar intensity radiation during day time was computed on every first day of the experiment. The graphs of solar intensity radiation were plotted against time for the study of the variation in intensity for various air flow rates.

Variation of solar radiation intensity when mass flow rate of 0.01484kg/sec is considered

Time am/pm	Solar Radiation Intensity(W/m^2)	
	With TES	Without TES
10.00	653	643
10.30	727	711
11.00	813	793
11.30	873	850
12.00	950	931
12.30	967	945
1.00	990	970
1.30	970	945
2.00	920	910
2.30	852	840
3.00	772	760
3.30	688	670

4.00	568	550
4.30	502	480
5.00	465	455

Table 1: Variation of intensity of solar radiation for mass flow rate = 0.01484kg/s



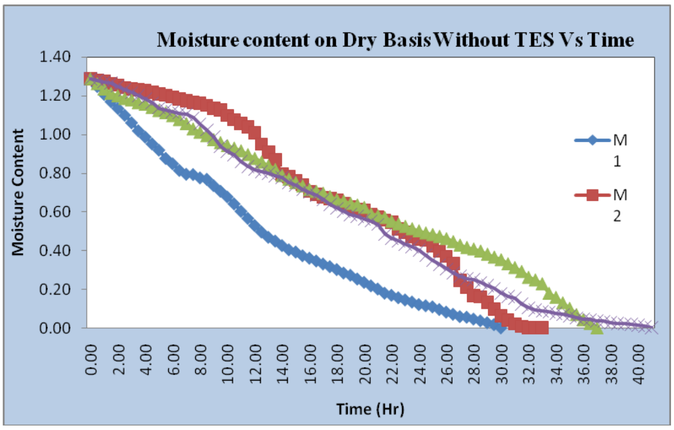
Graph.1: Variation of intensity of solar radiation vs. time formass flow rate = 0.01484kg/s

The experiments were conducted for several days, so in accordance to study intensity of the solar radiation on the day of the experiment performance, the intensity of solar radiation was measured using Pyranometer and plotted against time for each experiment. Experiment was conducted using mass flow rate of 0.01484kg/s, 0.01569kg/s, 0.01650kg/s and 0.01726kg/s. Intensity of the solar radiation remained approximately same for the everyday of the experiment performance. The temperature varies in relation with the solar radiation intensity. The average solar radiation intensity considered for the energy calculations is 800W/m^2.

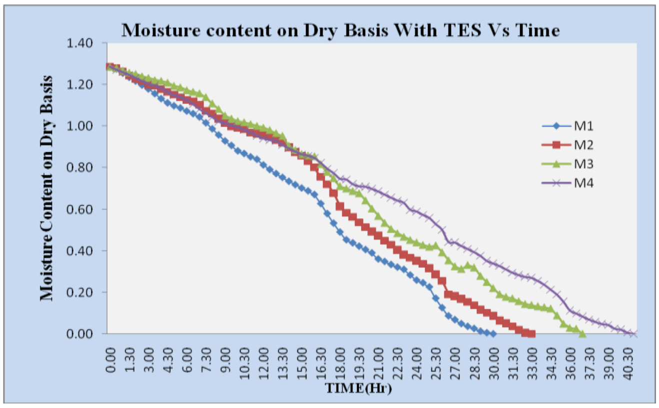
6.2 Variation of moisture content on dry basis with time

The study of variation is the moisture content on dry basis is done by plotting the graph of moisture content calculated on dry basis versus time. The moisture variation is calculated for the considered mass flow rates, it also gives an idea of effect of mass flow rate on drying rate. The comparison study is done by plotting the moisture content on dry basis for the flow rates M1=0.01484kg/sec,M2=0.01569kg/sec,M3=0.0165kg/sec & M4=0.01726kg/sec versus the drying time. The same comparison study is carried out for grapes with and without TES. The graph easily interprets the effect of the flow rate on the drying time.

The variation in the moisture content of the grapes without TES is studied by plotting of the moisture content calculated on dry basis versus time.



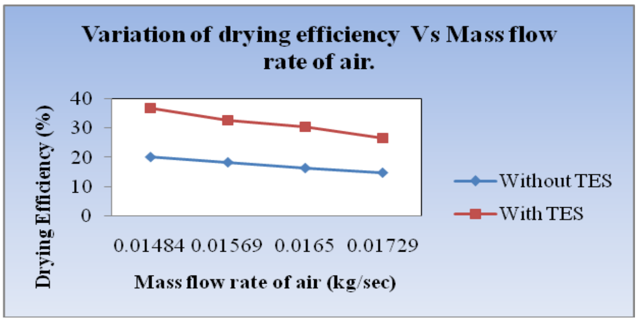
Graph 2: Variation in moisture content (dry basis) vs. time for grapes without TES



Graph 3: Variation in moisture content (dry basis) vs. time for grapes with TES

From the above graphs of moisture content on dry basis grapes, with and without TES versus time for the four mass flow rates, it is easily depicted that the moisture content decrease considerably with increase in the mass flow rate of air. The minimum drying time required for grape is 30 hours for the minimum mass flow rate of 0.01484kg/sec. and the maximum required drying time is 41 hours for the highest mass flow rate of 0.01726kg/sec.

6.3 Variation of drying efficiency with and without TES



Graph 4: Variation in drying efficiency with mass flow rate of air

The graph shows variation in dryer efficiency with mass flow rate of air with and without incorporation of thermal energy storage system. It is clear that incorporation of thermal energy storage system in the solar dryer reduces the drying time in terms of sunshine hours. Reducing mass flow rate of air reduced drying time and thus it enhances the dryer efficiency. With increase in mass flow rate of air, the temperature of the air at out of collector is going to decrease which reduces the drying temperature and thus enhances the drying time.The maximum dryer efficiency obtained is 36.64 % at mass flow rate of air 0.01484 kg/sec.

7 Conclusion and Recommendations

In this work mixed mode forced convection solar grape dryer with thermal energy storage has been developed and tested experimentally. The grapes with pretreatment have been dried with developed solar dryer. The designed dryer was integrated with a Phase Change Material to extend the use of dryer in the evening/night hours. The effect of air mass flow rate on moisture content, moisture ratio, drying rate, drying time and dryer efficiency has been evaluated for grapes. At the same time effect of thermal energy storage on drying time on grapes also evaluated with and without incorporation of thermal energy storage with variation in mass flow rate of air.

The following conclusions have been arrived at, from the experimental investigation carried out in the present work on solar grape dryer.

- Dried grape (Raisins) production is possible with developed solar dryer in much shorter time. An indirect type of solar dryer with forced air circulation can be used to produce superior quality raisins acceptable in the international market.
- The drying experiment conducted with grapes and it was found that the complete drying process could be attained with 30 hours, which is very less compared with open sun drying
- Incorporation of thermal energy storage system reduces drying time remarkably in terms of sunshine hours. With implementation of thermal energy storage the drying time for particular day can be extended from sunshine hours to non-sunshine hours. Hence it increase the quantity of products dried.
- With increase in mass flow rate of air the outlet air temperature of collector is going to decrease which reduces the drying temperature required and thus increases drying time
- After all this work put forward extension of renewable energy based drying technology in the field of grape drying so that small scale farmers can be economically benefited.

After performing the experiment with developed solar grape dryer the recommendations are as follows

- Thermal energy storage must be implemented for drying purpose which reduces the drying time in terms of sunshine hours drastically.
- Mass flow rate of air must be kept as low as possible considering the outlet air temperature so that reduced drying time with increased efficiency can be obtained.
- As observed in literature the drying time drastically reduces with pretreatment same results are also obtained with this experimentation also.

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