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THERMAL PERFORMANCE OF NATURAL CONVECTION SOLAR AIR HEATER WITH THERMAL STORAGE FOR DRYING AGRICULTURAL PRODUCE

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Abstract: *The solar cabinet dryer was developed and evaluated its thermal performance with and without heat storage system for drying tomato slices. The loading capacity of the dryer was about 10 kg slices per batch. The drying characteristics of the dryer were studied and compared with open sun drying method. Drying time for drying tomato slices from initial moisture content of 94% to final moisture content of 8.97% (wb) was found to be 12.0 h and 12.5 h in the solar cabinet dryer without and with heat storage system, respectively whereas, it was found to be 15 h in the open sun drying method. The powder was prepared from tomato slices dried in dryer and which shows the dark red colour compared to OSD dried slices powder. It was found that the gravel with iron scrap heat storage system supplied heat to the drying chamber for about 3 h after sunset also.*

Keywords: *Thermal properties, Compressive Strength, elevated Temperature, Fire Induced spalling*

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INTRODUCTION

Agriculture is considered to be the backbone of Indian economy as 65 to 70% of the population depends on agriculture for employment and livelihood. But, yet the national food production could not meet the needs of the population. In India, sun drying is the most commonly used method to dry the agricultural material like grains, fruits and vegetables. In sun drying, the crop is spread in a thin layer on the ground and exposed directly to solar radiation and other ambient conditions. The rate of drying depends on various parameters such as solar radiation, ambient temperature, wind velocity, relative humidity, and initial moisture content of produce, type of crops, crop absorptive and mass of product per unit exposed area (Mohanraj and Chandrasekar, 2008; Mohanraj and Chandrasekar, 2009[a,b]). This form of drying has many drawbacks such as degradation by windblown, debris, rain, insect infestation, human and animal interference that will result in contamination of the product. Drying rate get reduced due to intermittent sunshine, interruption and wetting by rain. At the time of harvesting, most of the agricultural products have high moisture content. Agricultural products, if left as such will biologically degrade due to the growth of microorganisms. So, to preserve them for future purpose and to make it available throughout the year proper preserving technique is to be adopted (Umayal Sundari et *al*., 2013).

Solar energy is a time dependent energy resource. Energy storage provides means for improving the performance and efficiency of vide range of energy systems. Solar dryer reduces operating cost by input of solar heat energy as compared to the electrical dryers. Solar dryer reduces drying time as compared to the traditional open sun drying. In many cases continuous drying is preferred. However, solar dryers are operated only during day time for 8-9 h. The conventional source of energy is to be used to continue for drying after sun set. Normally thermal storage systems are employed to store the heat, which includes sensible and latent heat storage. Common systems used in storing thermal energy include gravel bed, rock beds, sand, concrete etc., where thermal energy is stored in the form of sensible heat (Ataer, 2006; Anuradha and Oommen, 2013; Ayyappan and Mayilsamy, 2012; Kamble *et al.* 2013). Use of gravel and iron scrap bed for the improvement of performance of solar air heater has been proposed by several investigators (Saravankumar and Mayilsamy, 2010). Energy storage is essential for places where the solar intensity is high and need to be stored to avoid over-drying of the product and to continue the drying operation in off sunshine hours also (Dhote and Thombre, 2013).

Solar energy is by far the most attractive alternative energy sources for the future. But the main problem of solar energy is its intermittent nature. Hence provision of some device which could store this energy and supply it during off sunshine hour was made. Utilization of solar thermal energy through solar dryer is relatively new technology for drying of agricultural produce. The use of heat storage material in solar cabinet dryer such as gravels, sand, iron scraps, etc. provide the heat after sun set also. Therefore, the study was undertaken to develop solar cabinet dryer with and without heat storage system and to evaluate its thermal performance for drying tomato slices.

MATERIALS AND METHODS

A solar cabinet dryer of 10 kg per batch capacity was developed and installed in Department of Unconventional Energy Sources and Electrical Engineering, Dr. Panjabrao Deshmukh Krishi Vidyapeeth, Akola. The performance of the dryer with and without heat storage syste was evaluated for drying of tomato slices. The schematic and sectional views of solar cabinet dryer integrated with heat storage system are shown in Fig.1.

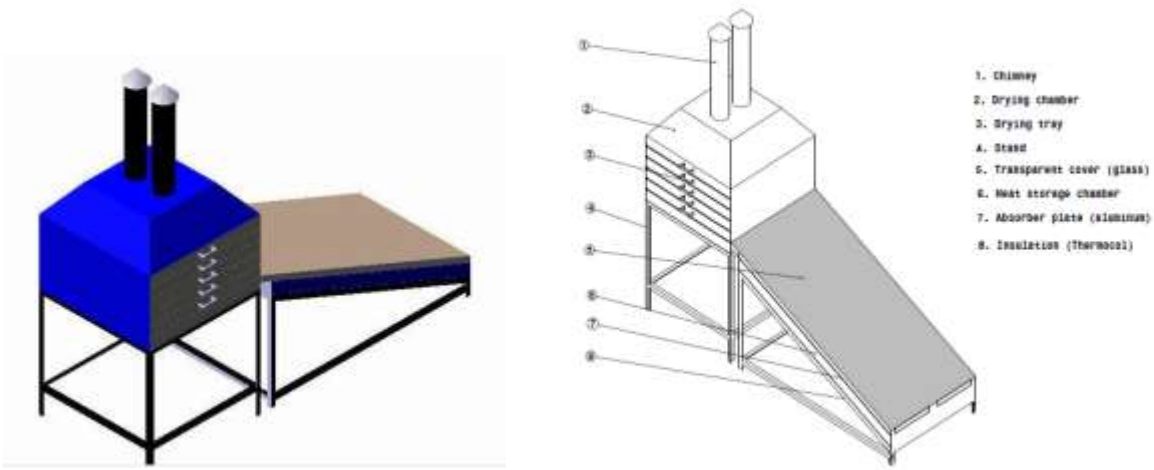

Fig.1 Schematic views of the solar cabinet dryer with heat storage system

Flat plate solar collector

A flat plate solar collector acts as solar air heater. The flat plate solar collector is directly connected to drying chamber. A natural air was circulated through the gap between transparent glass cover and absorber plate by simple thermo-syphon effect. The flat plate solar collector was placed on stand with an angle of 25° with respect to horizontal. The system was oriented to face south to maximize the solar radiation incident on the solar collector. To increase the temperature of air by greenhouse effect, toughen textured glass cover was used and it was placed on the top of the flat plate collector. The aluminum absorber sheet of 3 mm thick was used in solar air heater. The aluminum absorber sheet was coated with black paint in both sided to absorb the maximum incident solar radiation. The absorber plate was placed below the transparent cover with a layer of air separating it from the cover.

Heat storage system

A heat storage chamber was filled with heat storage materials like gravel and iron scrap to store heat during sunshine hours and to obtain hot air after sunset. The heat storage chamber was directly placed below the aluminum absorber plate. It acts as a heat exchanger and it was made up of 22 gauge GI sheet. To reduce heat losses the system was properly insulated using 5 mm thick thermocol. Insulation was provided below the heat storage chamber to avoid the heat losses from heat storage material.

Drying chamber

A drying chamber was designed for loading drying produce. The drying chamber was made up of 24 gauge CR sheet of 1.0 x 1.0 x 0.6 m. The holding capacity of drying chamber was 10 kg per batch. The drying chamber consists of five numbers of perforated mesh trays of size 1.0 x 1.0 m. It was made up of stainless steel wire mesh of 40 mesh per square inch and of 30 gauge. The holding capacity of each drying trays was about 2 kg. Two numbers of chimney with 0.15m in diameter and 0.75 m in length was provided on the top of drying chamber for release of moist exhaust air.

Ambient air, collector heat storage bed and drying chamber temperature solar cabinet dryer were measured with digital type RTD (resistance temperature detector) and 12 channel indicator. A solar radiation at the inclination of the dryer was measured with digital pyranometer with data logger. Relative humidity was monitored with digital hygrometer. A wind vane anemometer was used to measure the wind speed at the chimney of the dryer. The weight loss of tomato slices in the dryer and open sun drying method was measured periodically by digital electronic weight balance. The moisture content of the slices was measured by oven drying method. The observations of the dryer were recorded at 30 min. intervals.

Performance evaluation of solar cabinet dryer

Fresh air entered in the air heater and gets heated when comes in contact with the absorber aluminium plate and proceed to the drying chamber. Just below the aluminium plate sheet a heat storage system containing gravels and iron scrap material which absorbed the heat when sun radiation strikes on the aluminium sheet through glass and this stored heat was supplied to the drying chamber after sunset. Freshly harvested tomatoes were properly washed in fresh running water and then they were cut into slices of 4 to 6 mm thickness of tomatoes manually.

The performance of solar cabinet dryer was carried out with and without heat storage system at full load condition. The drying trays were loaded with 10 kg tomato slices and spread over the drying trays. Drying was conducted between 08:30 to 17:30 h. The experiment was conducted in the month of April and May 2014 for drying tomatoes slices. The initial weight of the samples was recorded. Each sample of 100 gm was weighted regularly at an interval of 30 min. and simultaneously the temperature, relative humidity, solar radiation and wind velocity inside the solar cabinet dryer and ambient temperature was measured. Tomato slices were loaded in the drying trays of the solar cabinet dryer and is shown in Fig. 2.

Fig. 2 Tomato slices loaded in solar cabinet dryer

Drying characteristics of tomato slices

The drying depends on simultaneous heat and mass transfer phenomena and factors dominating each process determine the drying behavior of the product. The drying rates were computed from the experimental data and drying characteristics curves i.e. moisture content versus drying time, drying rate and moisture ratio versus drying time.

The moisture ratio of the produce is computed by following formula (Chakraverty, 1988).

$$\text{Moisture Ratio (M.R.)} = \frac{(M_t - M_e)}{(M_i - M_e)} = e^{-kt}$$

Where,

M_t - Moisture content (db), %

M_e - Equilibrium moisture content (db), %

M_i - Initial moisture content (db), %

k - Drying rate constant per minute

t - Drying time, min

The drying rate, (m_w) was determined from the mass of moisture removed and drying time and was determined by the following equation.

$$m_w = \frac{M_w}{t_d}$$

Where,

m_w - Drying rate, kg h^{-1}

M_w - Quantity of water evaporated from product, kg

t_d - Assumed drying time, h

RESULTS AND DISCUSSION

Full load testing of solar cabinet dryer without heat storage system for drying tomato slices

The solar cabinet dryer without heat storage system was evaluated for drying of tomato slices. The maximum temperature in the solar cabinet dryer was observed to be 53.2°C whereas, the maximum ambient temperature, relative humidity and solar intensity were observed to be 42.1°C, 20.6% and 946.7 W/m^2, respectively (Fig. 4). Akachukwu, (2013[a,b]) has reported the average daily solar dryer temperature of 49.9˚C while drying tomato slices in small scale direct mode natural convection solar dryer. The flow rate of air at ambient condition and at the exhaust chimney was observed in the range of 0.4 to 1.13 and 0.1 to 0.2 m/s respectively. From Fig.3. it is clear that the temperature inside the solar cabinet drying chamber was significantly higher than open sun drying (OSD). It migth be due to the better absorption of solar energy by product as most of the solar energy entering the cabinet is trapped inside the cabinet solar dryer facilitating absorption and the chimney facilitates the removal of moisture by natural circulation of atmospheric air. This explicity indicates that the drying rate of tomato slices in the solar cabinet dryer was higher than that of OSD experiment.

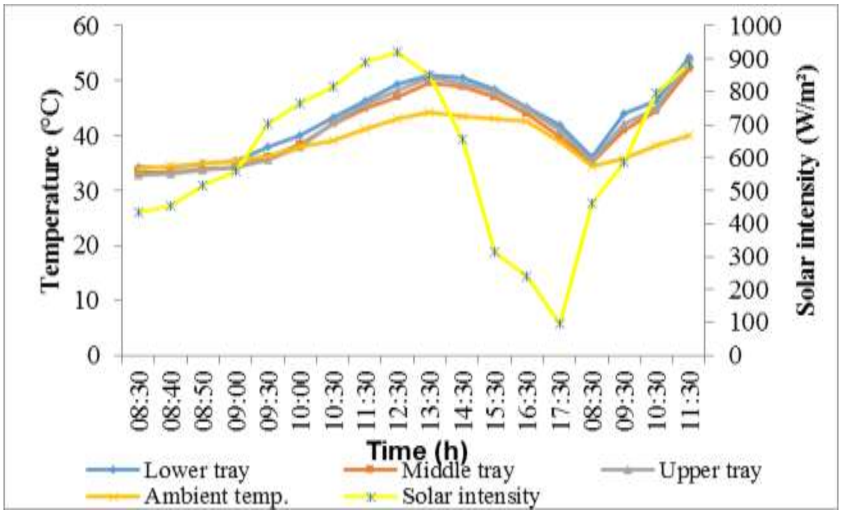

Fig 3. Temperature variation in the solar cabinet dryer without heat storage system during full load condition of tomato slices drying

From Fig.5 it is observed that the total drying time required for drying tomato slices was 12 h in solar cabinet dryer whereas, it was 15 h in OSD. The drying time was reduced to about 20% for drying tomato slices in solar cabinet dryer without heat storage system than OSD. From Fig.4 it depicted that the average moisture content of tomato slices placed in T1, T2, T3, T4 and T5 drying trays reduced from 1566.67 to 9.78% (db) was reached in 12 h. in solar cabinet dryer without heat storage system. Whereas, the average moisture content of tomato slices was reduced from 1566.67 to 12.91 % (db) in 15 h in OSD.

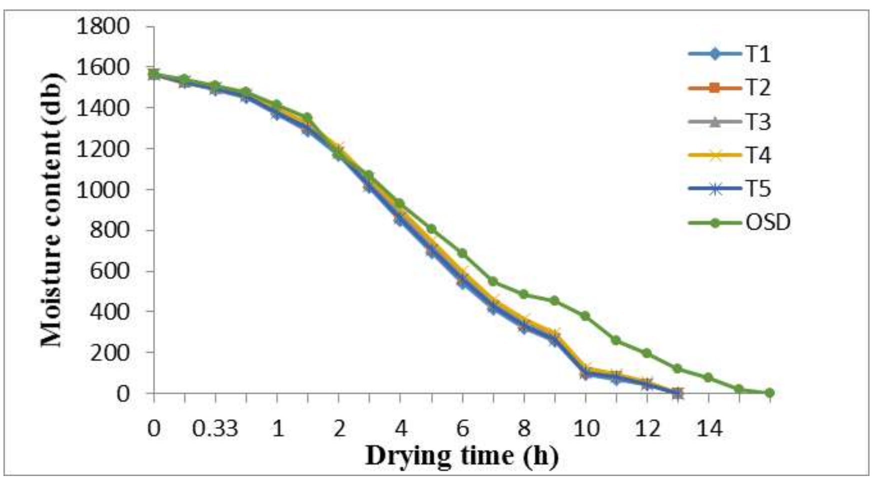

Fig 4. Variation of moisture content of tomato slices in solar cabinet dryer without heat storage system and OSD

From Fig. 5 it is seen that the drying rate of tomato slices dried in trays T1, T2, T3, T4 and T5 of solar cabinet dryer without heat storage system varied from 4.167 to 0.024, 4.278 to 0.027, 3.889 to 0.032, 3.333 to 0.036 and 4.167 to 0.025 gm/100gm bdm min, respectively. The drying rate of tomato slices dried in OSD was found to be 2.722 to 0.007 gm/100gm bdm min.

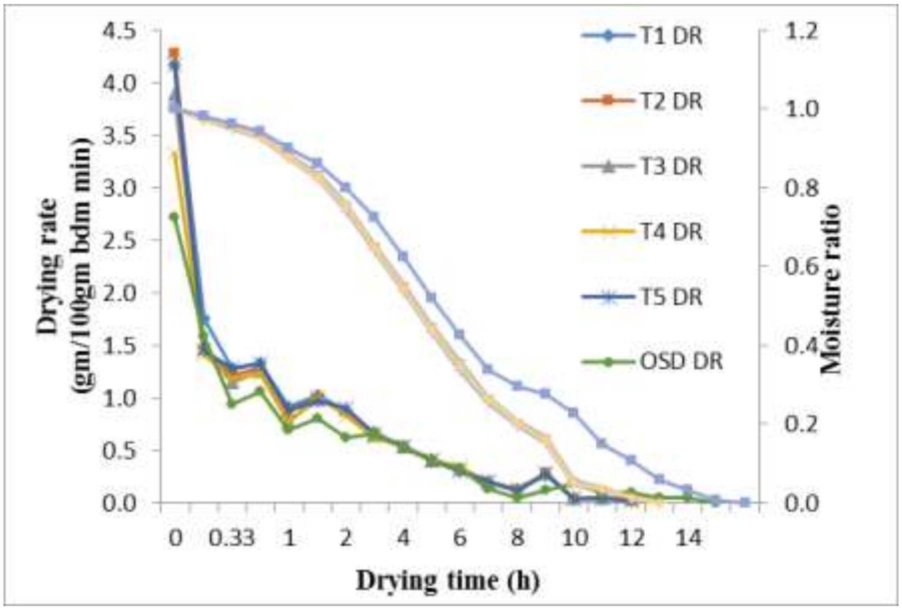

Fig 5. Variation of drying rate and moisture ratio of tomato slices in solar cabinet dryer without heat storage system and OSD

Solar cabinet dryer with heat storage system

The solar cabinet dryer with heat storage system was tested for drying of tomato slices. The maximum temperature attained in solar cabinet dryer was 52.63 whereas, the maximum ambient temperature and solar intensity was recorded as 42.03°C and 991.70 W/m^2, respectively. It was observed that drying of tomato slices in solar cabinet dryer took 12.5 h. From Fig.6 it is seen that the heat storage system supplied the heat after sunset hour also and remarkable difference in temperature of drying chamber and ambient was obsereved upto 20:30 h. and the drying of tomato slices was achieved in one day only (08:30 to 20:30 h).

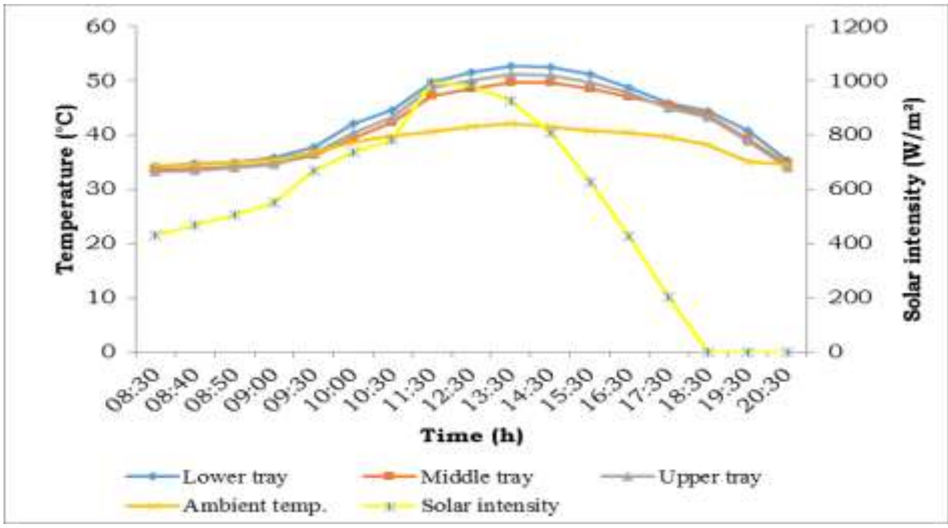

Fig. 6 Temperature variation in the solar cabinet dryer with heat storage system at full load condition

Tomato slices were dried in solar cabinet dryer and its drying characteristics were studied. Figure 7 revealed that the average moisture content of tomato slices samples placed in T1, T2, T3, T4 and T5 trays reduced from 1566.67 to 9.78% (db) in 12.5 h in solar cabinet dyer with heat storage system. Whereas, the average moisture content of tomato slices sample reduced from 1566.67 to 12.91 % (db) in 15 h for open sun drying in the month of May 2014. Babagana *et al*. (2012) reported the drying time of 14 hrs for tomato slices in solar vegetable dryer with heat storage system.

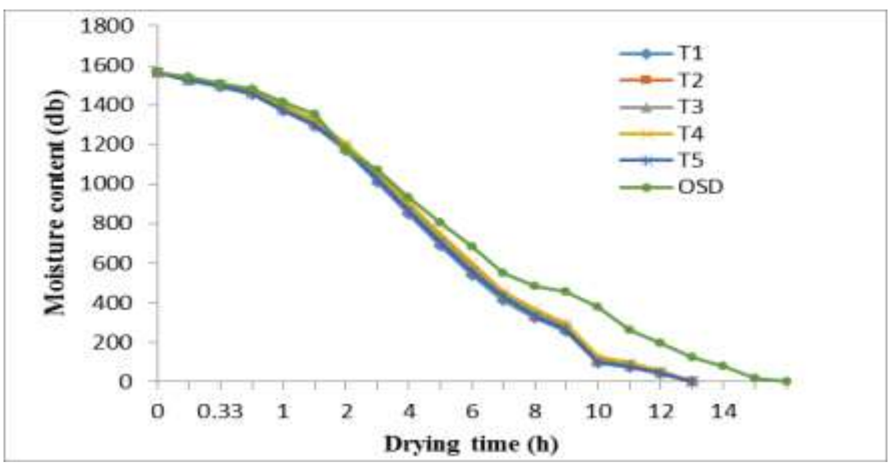

Fig7. Variation of moisture content of tomato slices in solar cabinet dryer with heat storage system and OSD

Figure 8 revealed that the average drying rate of tomato slices dried in T1, T2, T3, T4 and T5 trays of solar cabinet dryer integrated with heat storage system was found to be 0.9233, 0.8821, 0.8390, 0.7889 and 0.8132 gm/100gm bdm min, respectively. The drying rate of open sun dried tomato sample (OSD) was found to be 2.3889 to 0.0111 gm/100gm bdm min.

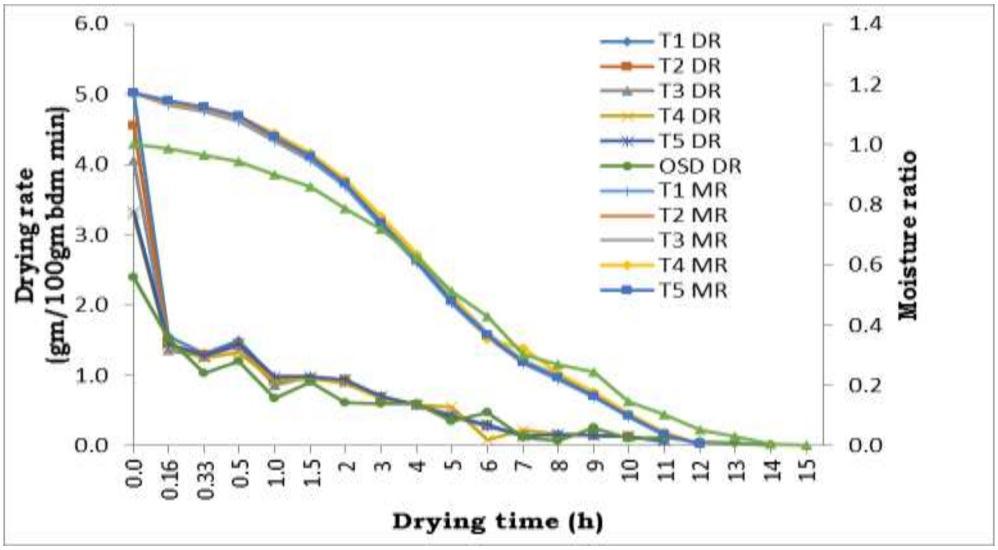

Fig 8. Variation of drying rate and moisture ratio of tomato slices in solar cabinet dryer with heat storage system and OSD

Temperature developed in heat storage system of solar cabinet dryer

The temperature developed in the heat storage system of solar cabinet dryer during day time and after sunset was measured at full load condition at upper and lower layer of heat storage system viz., bottom, middle and top. From Fig.10 it is seen that the maximum temperature in the heat storage system at its upper layer was observed to be 73.97°C while, the temperature in the heat storage system at its lower layer was observed to be 60.83°C. The maximum ambient temperature was observed to be 42.03°C and solar intensity was 991.70 W/m^2.

The maximum temperature difference between ambient and drying chamber was 10.83 during 08:30 to 17:30 h and it was observed 8.18 to 5.87°C during 17:30 to 20:30 h for tomato slices drying in solar cabinet dryer with heat storage system. Senthilkumar et al. (2013) reported to maintain consistent temperature inside the collector even during off shine hours (17:00 to 19:00h).

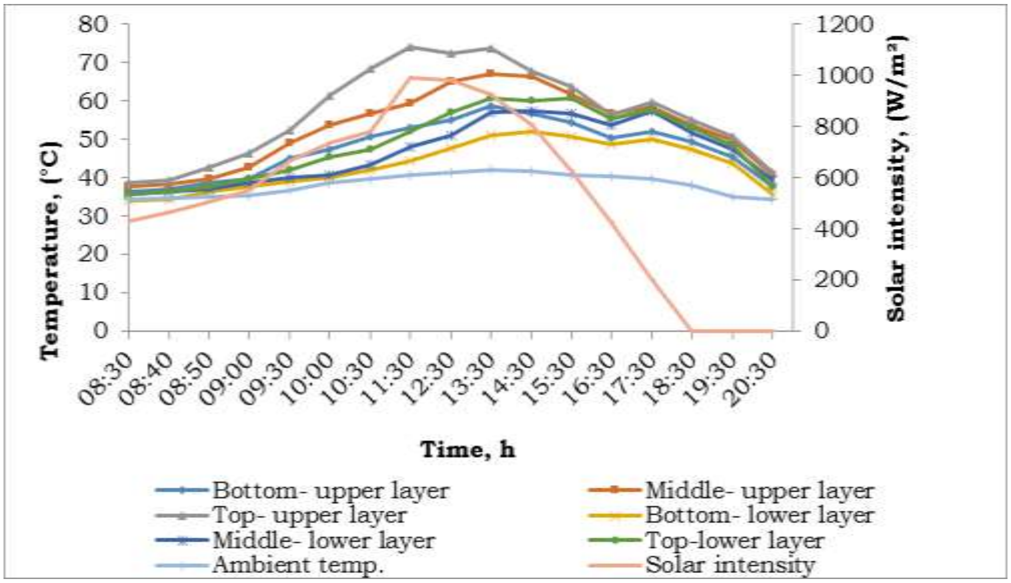

Fig 9. Temperature developed in the heat storage system at full load condition in May, 2014

Variation in moisture content in solar cabinet dryer and OSD method

The variation of moisture content (db) with drying time is illustrated in Fig. 10. Drying time for drying of tomato slices from initial moisture content of 94 to 8.91 % (wb) i.e. 1567 to 9.78% (db) was found to be 12.5, 12 and 15 h in solar cabinet dryer with heat storage system, dryer without heat storage system and OSD methods, respectively.

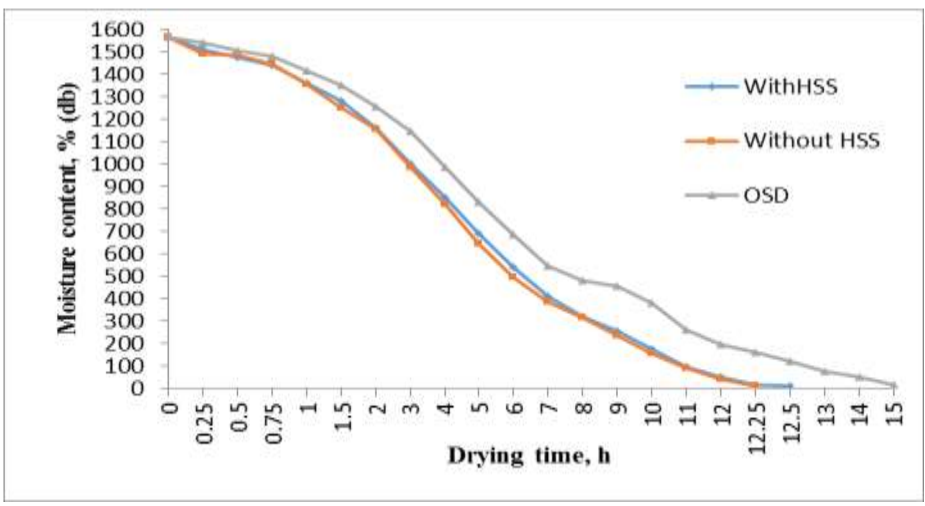

Fig.10 Variation in moisture content in solar cabinet dryer and open sun drying of tomato slices

Appearance of dried tomato slices and powder

The drying of tomato slices was carried out in solar cabinet dryer with heat storage system and in open sun drying method. The appearance of slice of tomato dried in dryer and OSD is shown in Fig.12 (a) and (b), respectively. From Fig. 11 it is clearly observed the remarkable difference between tomato slice dried in dryer and OSD. The powder was prepared from tomato slices dried in dryer and which shows the dark red colour compared to OSD dried slices powder (Fig. 13).

(a) Open sun dried tomato slices

(b) Solar cabinet dried tomato slices

Fig. 11 A view of dried tomato slices in open sun and solar cabinet dryer

Open sun dried tomato powder

Solar cabinet dried tomato powder

Fig. 13 A view of dried tomato slices powder in open sun and solar cabinet dryer

Economics of solar cabinet dryer for drying of tomato slices

The economic feasibility of solar cabinet dryer with and without heat storage system for drying of tomato slices was calculated by considering initial investment, depreciation cost, annual interest, average repair and maintenance cost, cost of raw material and tomato powder.

Economics of solar cabinet dryer with and without heat storage system for drying of tomato slices using different economic parameters are summarized in Table 1. Around 270 drying days are available for drying in one year. As the drying of one batch was completed in one and half drying day in solar cabinet dryer without heat storage system and therefore, total 180 numbers of batches could be completed in 270 drying days. Whereas, the drying of tomato slices was completed in a single day in solar cabinet dryer with heat storage system and hence 270 batches of drying could be possible in a year.

Table 2. Cost economics of solar cabinet dryer for drying tomatoes slices per year

S. N.	Description	without heat storage	With heat storage system
1	Life of dryer, Year	10	10
2	No. of drying days in a year	270	270
3	No. of drying batches per year	180	270
4	Tomato slices loading capacity, kg (10 kg/batch)	1800	2700
5	Initial investment for dryer, Rs.	30000	32000
6	Depreciation cost @ 10% per annum	3000	3200
7	Interest @ 10% per annum	3000	3200
8	Repairs and maintenance cost, Rs. (2% per year)	600	640
9	Cost of raw material i.e. tomatoes @ Rs. 8/kg (Rs yr^{-1})	14400	21600
10	Cost of labour for drying @ Rs180/day (Rs yr^{-1})	32400	48600
11	Total dried powder, kg per annum	216	324
12	Cost of grinding powder @ Rs 3 per kg	648	972
	Total Cost, Rs.	**54048**	**78212**
13	Total cost of finished product, Rs. (Average market value @ Rs 350/kg)	75600	113400
	Net Benefit, Rs	21552	35188
	Benefit- cost ratio	1.40	1.45

Payback period	16 months	11 Months

The BC ratio of the solar cabinet dryer without heat storage system was worked out to be 1.40 whereas, it was found to be 1.45 for the solar cabinet dryer with heat storage system (Table 2.). The payback period of the of the solar cabinet dryer without heat storage system was estimated to be 16 months whereas, it was found to be 11 months in case of solar cabinet dryer with heat storage system.

CONCLUSIONS

Drying time for 10 kg of tomato slices for reducing its moisture content from 94 to 8.97% (wb) was found to be 12.0 h and 12.5 h in the solar cabinet dryer without and with heat storage system, respectively whereas, it was found to be 15 h in the open sun drying method. The BC ratio and payback period of the solar cabinet dryer without heat storage system was worked out to be 1.40 and 16 months and it was found to be 1.45 and 11 months for dryer with heat storage system. It was observed that the gravel with iron scrap heat storage system helped to continue the drying for about 3 h after sunset also.

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