Performance analysis of solar air dryer for drying different spices

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Abstract. The present work is confined to the fabrication of a solar dryer for drying spices and evaluates the performance of the collector and dryer system. The materials for each component of the dryer system is chosen considering different parameters effecting the performance of the dryer which includes design, operational, meteorological and environmental parameters. The experiments were carried out for 1 kg of two different types of spices and the drying efficiency is estimated to be 3.81 % for red chilly and 2.04 % for turmeric. The collector temperature is varying between 58ºC to 90ºC and the drying chamber temperature is varying between 46ºC to 60ºC during the entire observation period for an ambient temperature of 36ºC to 41ºC. The collector efficiency is varied from 28% to 45 %. The variation in moisture content and drying rate over the drying period are analysed and presented.

Keywords—Natural convection, Spices, Overall drying efficiency, Moisture content, Drying rate, Type-K thermocouple, DHT22 humidity sensor, Lithium-ion rechargeable cell.

1. Introduction
Solar energy is the primary source of energy which is clean, abundant and inexhaustible in nature. India is endowed with abundant solar radiation. The total solar radiation incident on the country is 5000 trillion kWh/year, which is many times more than its yearly total energy requirement [1]. This lavish energy can be harnessed in two forms either photovoltaic conversion or solar thermal conversion. Solar thermal conversion i.e. the use of heat energy from the sun for water heating, space heating, steam generation in thermal power plants and energy efficient buildings have already acquired great acceptance over the world [2, 3].

Drying of certain vegetables, crops, spices and fruits which have high moisture content is essential for long term storage. Reducing the water content by drying is a preventive measure against microbial or fungal attack. Drying is achieved at high temperatures using hot air, electric heating or mechanical drying which consumes large amount of energy. Hence using solar energy for drying at different industries could cut down the use of high price conventional energy which is in the depletion period. Drying under open sun is in use from ancient times. However, open sun drying is not very efficient due to various contaminations. Solar dryer is the utilization of solar energy for drying commodities in a more efficient way. There are several solar dryers developed by different researchers for drying...
different products. P. Barnwal and G.N. Tiwari [4] has designed a hybrid photovoltaic- thermal greenhouse dryer for drying 100 kg of grapes by forced convection using a DC fan driven by a 20 W PV module. The moisture evaporation for greenhouse, open and shaded condition is compared for Thompson seedless grapes. S. Nabnean et al [5] has developed a solar hybrid dryer using water type solar collector, heat exchanger and solar hot water storage tank for drying osmotically dehydrated cherry tomatoes from initial moisture content of 62% wet basis(w b) to final moisture content of 5 % wet basis (w b) in 4 days. The temperature of the drying chamber varies from 30 °C to 65 °C. S Dhanuskodi et al [6] have developed a biomass dryer for cashew nut processing. Experimental data revealed that moisture content of cashew nut has been reduced from 9 % wet basis to 4% wet basis in 7 hours whereas it took 15 hours in case of open sun drying. Also the dryer produces temperature in the range of 70 °C to 75°C continuously. Wade et al [7] had done a comparative study of drying characteristics of chilly in open sun drying, indirect solar cabinet dryer, solar tray dryer and hot air oven and found the highest rate of drying in solar tray dryer. Variation of moisture content of both red chilly and green chilly with respect to drying time is presented. M.S. Deveda and Deepak Jhaharia[8] has developed a solar dryer for drying large cardamom and obtained a 55.7% higher temperature than ambient . Moisture content of cardamom was reduced from 75.6% wet basis to 10 % wet basis in 24 hours compared to 48 hours in open sun.

The present work is to develop a natural convection solar dryer for drying spices for small scale entrepreneur completely based on solar energy at very less investment which does not involve any supplementary energy. Since drying of spices does not require very high range of temperature which can be achieved with natural convection. So that high export quality product could be achieved. Based on the method of heating and modes of utilization of solar energy solar air dryers are classified into following different types [9, 10].

i) Passive solar dryer: Passive solar dryers are natural convection solar dryers where ambient air is heated by the solar collector and is circulated naturally by means buoyancy forces.

ii) Active solar dryer: Active solar dryers are forced convection solar dryers. It uses solar energy as the primary heat source and a fan or blower is used to enhance the circulation of hot air to increase the rate of heat transfer. The blower can be powered using either PV module or it can use grid electricity.

iii) Hybrid solar dryer: Hybrid solar dryers utilize solar energy as well as either biogas or conventional source of energy to heat the ambient air when solar energy is not sufficient.

iv) Direct solar dryer: In direct mode of solar drying the product is directly exposed to solar radiation.

v) Indirect solar dryer: The product to be dried is kept in trays in a separate drying chamber. Ambient air is heated in a solar collector from where it flows into the drying chamber either by means of forced convection or by natural convection.

vi) Mixed mode solar dryer: In case of mixed mode solar dryer both direct mode and indirect mode of drying is incorporated.

2. Experimental setup
The experimental setup for the present work is completed in the indigenous projects lab under project office in Amrita Vishwa Vidyapeetham, Coimbatore as per the design developed.

2.1. Proposed model
The proposed model consists of a collector which absorbs heat from the solar radiation and transfers the heat to the air. The collector comprises of a single glass cover and the air is flowing through the duct between the absorber plate and bottom plate. The heated air is then passed through the drying chamber where the product to be dried is kept in the tray. The product absorbs heat from the hot air and moisture is released. The product temperature will increase with time and the moisture content decreases. The hot air after absorbing moisture from the product escapes through a chimney at the top.
2.2 Materials and dimensions
The collector is designed having an area of 0.5 m² with an air vent area of 0.3 m². The glass cover is made of 4mm thick plain glass with high transmissivity so that maximum solar radiation is transmitted through it to the absorber [11]. The absorber plate and the bottom are made of black painted aluminum to increase its absorptivity [12]. The spacing between the absorber plate and glass cover is kept as 4cm [11], [13]. Polyurethane foam insulation of 2 cm thick is used between the bottom plate and the frame to prevent heat loss from the bottom plate since its conductivity is less. The drying chamber is made spacious with a drying floor area of 0.5 m² and volume of 1m×0.6m×0.5m. The entire collector frame and drying chamber walls are made of water resistant plywood of 12mm thickness. Plywood is cheaper in price compared to mild steel or galvanized steel also plywood has low heat conductivity of the order of 0.13 W/ m K. Hence it can retain the heat and acts as heat storage material which ensures a quantified amount of moisture reduction during night when sun is not available. In order to prevent any moisture absorption the plywood is painted black from inside. One single tray of net wire mesh of dimension 0.7m×0.3m is fixed inside the drying chamber. The top portion of the chimney as well as the air vent front side is covered with net wire mesh.

2.3 Equipments used
Three k-Type thermocouples are inserted at three different places of the fabricated unit, at the collector, one inside the drying chamber and one to get the ambient temperature respectively. One temperature and humidity sensor is fixed at the tray to get the relative humidity and temperature at the tray. Temperature at the drying chamber outlet is measured using GM816 digital anemometer. The temperatures as well as humidity at different places are displayed in a 16×2 LCD display. The sensors are interfaced with the 16×2 LCD using one ARDUINO UNO. Two numbers of Samsung ICR18650-26F Lithium–ion rechargeable cell is used to power the Arduino UNO. The solar radiation at the locality is measured using Luxmeter. Figure 1(a), (b), (c) shows the different views of the solar dryer designed in Autocad 2016.

![Figure 1(a). Top view.](image-url)
Figure 2 and figure 3 shows the pictorial view of the experimental setup and position of different sensors on the solar dryer.

3. Results and discussion

The fabricated solar dryer is located in the terrace of Renewable Energy Laboratory, Amrita Vishwa Vidyapeetham, Coimbatore campus, 11.0168° N, 76.9558°E. The temperature at different position of the solar air dryer, relative humidity and solar irradiance is observed in hourly basis for 8 hours in the locality in the month of March 2018 on a particular day under no load condition. The collector temperature is varying from 60 °C to a maximum of 92 °C and the drying chamber temperature is varying from 45 °C to a maximum of 57 °C when the solar irradiance is varying from 540 W/m² to a maximum value of 1150 W/m² on that particular day. Also the ambient relative humidity of 50 % has been reduced to 12 % inside the drying chamber. The efficiency of the collector is determined using equation (1)

\[
\eta = \frac{q_u}{I \times A_c}
\]  

(1)
Heat gained by the air determined at each hour by observing the ambient temperature \( T_a \) and temperature at the collector outlet \( T_c \). Mass flow rate of air is determined using equation (3), where air velocity is measured using a digital anemometer.

\[
\dot{m} = \rho A v
\]  

(3)

The density of air \( \rho = 1.225 \text{ kg/m}^3 \) and the air vent dimension \( A_v = 0.3 \text{ m}^2 \). The average efficiency of the collector is found to be 40.2%.

The performance testing of the dryer under loaded condition is done for two different varieties of product. The different drying curves are plotted and presented. Also the overall drying efficiency of the dryer under different drying conditions is evaluated.

### 3.1. Drying red chilly

Fresh varieties of 1kg red chilly obtained from the local market were washed properly and spread in shaded area to remove the water from the surface. The whole amount is then spread in the tray inside the drying chamber (DC) so that the tray surface area is fully covered. The samples are weighed each hour from morning 9.30 am to evening 3.30 pm to note the weight reduction. The process is continued till the weight of the chilly becomes constant. Figure 4(a) and 4(b) show photographs of raw and dried red chilly respectively. Results of drying red chilly for a typical day are shown in table 1.

![Figure 4(a)](image1)

![Figure 4(b)](image2)

3.1.1. Moisture content in red chilly. The initial and final moisture content of chilly is determined both in wet basis (%w b) and dry basis (%d b) using equations 4 and 5 respectively.

\[
\% \text{ moisture content (w b)} = \frac{m_w}{m_t}
\]  

(4)

\[
\% \text{ moisture content (d b)} = \frac{m_w}{m_d}
\]  

(5)
Table 1. A typical day results for drying red chilly.

| Time  | $T_a$ (ºC) | $T_C$ (ºC) | $T_{DC,i}$ (ºC) | $T_{DC,o}$ (ºC) | $T_{tray}$ (ºC) | Weight of the product (g) | Relative humidity inside (%) | Relative humidity outside (%) |
|-------|------------|------------|-----------------|-----------------|-----------------|--------------------------|-----------------------------|----------------------------|
| 9.30  | 36         | 58         | 49              | 38              | 46              | 230                      | 58                          | 22                         |
| 10.30 | 37         | 65         | 53              | 38              | 49              | 221                      | 50                          | 18                         |
| 11.30 | 37         | 70         | 55              | 42              | 50              | 209                      | 47                          | 11                         |
| 12.30 | 38         | 80         | 58              | 44              | 52              | 193                      | 42                          | 9                          |
| 1.30  | 39         | 88         | 58              | 41              | 55              | 186                      | 37                          | 8                          |
| 2.30  | 39         | 70         | 56              | 40              | 51              | 180                      | 36                          | 8                          |
| 3.30  | 38         | 61         | 53              | 40              | 50              | 171                      | 36                          | 7                          |

Where $m_w$, $m_t$ and $m_d$ is the mass of water present in the total quantity of the product, total mass of the product and dry weight of the product respectively. Dry weight of the product is obtained by oven drying the product till constant weight is obtained. The difference between the total mass of the product and the dry weight gives the mass of water to be removed by drying. The initial moisture content of the sample of 840 g used for experimentation is found to be 83.1 % (w b) and 435.03 % (d b) respectively. The samples are dried to a final moisture content of 4.26 % (w b) and 4.25 % (d b) respectively in 30 drying hours to a mass of 157 g. The moisture content variation over the entire drying period is shown in figure 5. The curve explains the reduction in moisture content in the product.

Figure 5. Moisture content variation of chilly over the entire drying period.
It can be seen that initially the moisture content is nearly constant with slight drop in moisture reduction each hour. But after reaching moisture content of 50% (w b) the moisture reduction follows a falling rate.

3.1.2. Drying rate of chilly. The drying rate is the rate of change of moisture content per unit time that explains the drying characteristics of the product. Drying rate is mostly influenced by the solar irradiance, amount of water present in the product, the surface area of the product. The variation in drying rate of red chilly is shown in figure 6 and figure 7.

![Figure 6. Variation of drying rate over drying period](image)

![Figure 7. Variation of drying rate with moisture content](image)

Figure 6 and figure 7 depicts that during the initial drying hours of chilly the drying rate reaches a maximum of 0.05 kg/h however with increasing time of drying it decreases to 0.002 kg/hour. During the initial drying hours evaporation of free moisture takes place from the product surface so the drying rate is high. However, drying rate slowly decreases as the critical moisture content is reached and ceases at equilibrium moisture content. During this period the moisture removal takes place from the
interior of the product to the surface. So the drying rate decreases. Also it is noted that the drying rate is increasing from morning till noon and then decreases towards afternoon. It is because the rate of moisture removal increases and decreases with the temperature of air inside the drying chamber based on which the surface temperature of the product varies.

3.2. Drying turmeric

![Figure 8(a).](image_url)

![Figure 8(b).](image_url)

Table 2. A typical day result of drying turmeric

| Time  | $T_a$ (ºC) | $T_c$ (ºC) | $T_{DC,i}$ (ºC) | $T_{DC,o}$ (ºC) | $T_{tray}$ (ºC) | Weight of the product (g) | Relative humidity inside (%) | Relative humidity outside (%) |
|-------|------------|------------|-----------------|-----------------|----------------|--------------------------|---------------------------|-----------------------------|
| 9.30  | 36         | 58         | 46              | 36              | 42             | 995                      | 67                        | 20                          |
| 10.30 | 37         | 66         | 51              | 38              | 49             | 939                      | 43                        | 12                          |
| 11.30 | 39         | 76         | 55              | 40              | 51             | 923                      | 37                        | 8                           |
| 12.30 | 40         | 85         | 58              | 44              | 54             | 903                      | 34                        | 5                           |
| 1.30  | 41         | 88         | 57              | 43              | 53             | 888                      | 28                        | 5                           |
| 2.30  | 39         | 84         | 56              | 40              | 51             | 858                      | 26                        | 5                           |
| 3.30  | 39         | 73         | 52              | 40              | 51             | 840                      | 24                        | 5                           |
| 4.30  | 38         | 67         | 50              | 39              | 48             | 829                      | 25                        | 4                           |
1 kg of fresh turmeric is washed and boiled in hot water till the rhizomes become soft. The stage at which boiling is stopped largely influences the colour and aroma of the product [14]. The cooked rhizomes are then spread to remove water from the surface in open area under shade. The samples are then weighed again and spread over the tray inside the drying chamber. The samples are weighed at interval of each one hour from 9.30 am to 4.30 pm to note the moisture reduction and the drying is continued till the weight becomes constant. The photographs of raw and dried turmeric are shown in figure 8(a) and 8(b). A typical day result of drying turmeric is shown in table 2.

3.2.1. Moisture content in turmeric. The initial and final moisture content has been found in the similar way as it done for chilly using equation 4 and 5. The weight of turmeric sample was 955 g initially and it is reduced to 245 g after drying. The turmeric with initial moisture content of 74.35% (w b) is reduced to 3.16% (w b) in 6 days i.e. 48 drying hours. The moisture content variation of turmeric is shown in figure 9 which explains the reduction in moisture content of turmeric over the entire drying period in hourly basis.

![Figure 9. Variation of moisture content over the drying period.](image)

3.2.2. Variation of drying rate of turmeric. The variation of drying rate and moisture content over the drying period explains the drying curves of the product. The rate of moisture removal for turmeric per unit time over the entire drying period and with moisture content variation is shown in figure 10 and figure 11.

From figure 10 and figure 11, it is noted that during the initial drying hours the drying rate of turmeric is high with a value in between 0.025 to 0.035 kg/h. But as the drying time increases the drying rate decreases and reaches a minimum value of 0.005 kg/h. This is the same reason as in case of chilly. Also similar way drying rate is influenced by the variation of drying air temperature inside the solar dryer which varies accordingly with solar irradiance. The drying rate increases from morning till noon and then decreases towards evening for each day.
3.3. Drying efficiency of the system
The overall drying efficiency is defined as the energy utilized to evaporate the moisture form the product out of the total energy available [6].

$$\eta_{overall} = \frac{L_v \times \Sigma m_w}{A_c \times 3600 \times \Sigma I \times t_d}$$  \hspace{1cm} (6)
The latent heat of vaporization at temperature $T$ °C is given by the following empirical relation:

$$L_v = 2502.5 - (2.386 \times T) \times 1000 \text{ kJ/kg}, \text{ at } 55^\circ C \quad L_v = 2371 \text{ kJ/kg}$$

The overall drying efficiency for red chilly and turmeric is given in Table 3.

### Table 3. Overall drying efficiency of the system.

| Product     | Initial mass (g) | Final mass (g) | Mass of water to be evaporated (g) | Drying time in hours | Drying efficiency (%) |
|-------------|------------------|----------------|-----------------------------------|----------------------|-----------------------|
| Red chilly  | 840              | 157            | 638                               | 30                   | 3.81                  |
| Turmeric    | 995              | 245            | 710                               | 46                   | 2.04                  |

### 4. Conclusion

The results show that the performance of the dryer is varying for different variety of products. Also, the collector efficiency lies in the range of 35% to 40%. The temperature obtained at the collector and the drying chamber is quite appreciable for drying spices which usually do not require very high range of temperatures. Also, drying time in solar dryer is reduced to a quite appreciable percentage compared to open sun drying. For red chilly it takes more than 40 hours [15] in case of open sun drying however it took less than 30 hours in solar dryer. Same is the case for turmeric when open sun drying takes 10-15 days [14], whereas solar dryer it took only 6 days.

The materials used for fabricating the dryer are not very costly. Also, plywood has the advantage of retaining heat with high thermal resistance value. Aluminum used for absorber plate and bottom plate is having high conductivity and black paint enhances the absorptivity and emissivity of the absorber and bottom plate. So, the heat transfer to the air increases and the efficiency of the collector is enhanced. The dryer designed in the present work produces temperature output that is in the useful range. Being simple, it is expected to be cheap with simple technology; hence, can be easily implemented by small scale entrepreneurs.

### References

[1] MNRE website
[2] Chaithanya K K, Rajesh V R, Rahul Suresh, 2016. Experimental analysis of desalination unit coupled with solar water lens concentrator, IOP Conf. Series: Materials Science and Engineering 149 012182 doi:10.1088/1757-899X/149/1/012182
[3] Rajesh V R, Harikrishnan K, Chaithanya K K and Subi Salim, 2016, March. Performance evaluation of solar desalination system integrated with Fresnel lens. International Journal of Renewable Energy Research (IJRER), Vol.6, no.1, pp.250-253.
[4] P. Barnwal, G.N. Tiwari, 2008. Grape drying by using hybrid photovoltaic-thermal (PV/T) greenhouse dryer: An experimental study. Solar Energy 82 1131–1144.
[5] Nabnean, S. Janjai b, S. Thepa, K. Sudaprasert, R. Songprakorp, B.K. Bala, 2016. Experimental performance of a new design of solar dryer for drying osmotically dehydrated cherry tomatoes. Renewable Energy 94 147e156.
[6] S. Dhanushkodi, Vincent H. Wilson and K. Sudhakar, 2015. Design and performance evaluation of biomass dryer for cashew nut processing. Advances in Applied Science Research, 6(8):101-111
[7] N. C. Wade, S. S. Wane and S. M. Kshirsagar, 2014. Comparative study of drying characteristics in chilly. Ind. J. Sci. Res. and Tech. 2(3):105-111
[8] M.S. Seveda and Deepak Jhajharia, 2012. Design and performance evaluation of solar dryer for drying of large cardamom (Amomum subulatum). Journal of Renewable and Sustainable Energy.
[9] R.J. Fuller, Solar Drying-A technology for sustainable agriculture and food production. Solar Energy Conversion and Photoenergy Systems.
[10] Om Prakash, Anil Kumar, 2017. Solar Drying Technology Concept, Design, Testing, Modeling, Economics and Environment. (Green Energy Technology).
[11] SP Sukhatme, JKNayak, SOLAR ENERGY Principles of Thermal Collection and Storage. (Solar Energy Third Edition)
[12] Table of emissivity of various surfaces (online) Available: http://www-eng.lbl.gov
[13] Karim, M.A., Hawlader, M.N.A, 2006. Performance evaluation of a v-groove solar air collector for drying applications. Applied Thermal Engineering 26 (2006) 121–130, June 2005.
[14] Turmeric processing, KAU Agri-Infotech portal. Available online @ www.celkau.in
[15] Ashish Kumar, Ajeet Kumar Rai, Jan–June 2016. Comparative study of open sun drying and solar cabinet drying techniques for drying of green chilies. International Journal of Production Technology and Management (IJPTM) Volume 7, Issue 1, pp. 18–26, Article ID: IJPTM_07_01_002.