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Performance of solar dryer for *Solanum lycopersicum* drying

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Abstract

Convective solar drying is an important food preservation technique which is cheaper and easier to operate, as compared to other food preservation methods. Due to contamination of food items by microbes, solar tunnel dryer provides the solution for an improved quality of products with better moisture removal capacity. Computational and experimental investigation was performed on a solar tunnel dryer (STD) for drying samples of *Solanum lycopersicum* in both cultivated and hybrid varieties. Effective reductions of moisture content can be found in the STD (91.5% to 4.001% in 31hrs and 4.266% in 27hrs) as compared to open sun drying (91.5% to 5.35% in 29hrs and 9.86% in 48hrs) in cultivated and hybrid varieties respectively. The relative humidity (RH) of the air inside the dryer was found to be 11% lower than the RH of ambient air. The results of the simplified model were compared with radiation surface to surface (S2S) model of a detailed and experimentally validated 3-D computational fluid dynamics model, which have shown the closeness of the experimental value with the predicted results. The quality of products obtained from the STD was of superior quality and provides longer shelf life.

Keywords: Solar tunnel dryer; *Solanum lycopersicum*; numerical validation

INTRODUCTION

Perishable food items are a major problem in today's world due to improper storage and preservation techniques. One of the most commonly used food preservation method is the convection drying. From time immemorial, convection drying is considered as a cheap and easy preservation technique. Due to abundance of solar energy, solar convective drying serves the purpose. Direct sun drying was first opted for preserving the foods and the results were quite satisfactory. But one of the major drawbacks in this type is the contamination by microorganisms present in the ambient air. To overcome this drawback, various researchers have performed convective solar drying on closed systems; one such is the solar tunnel dryer. Organic tomato were dried using solar tunnel dryer on the ecological conditions of Ankara, Turkey while achieving reduction of final moisture content from 93.35% to 11.50% in four days, as compared to five days in open sun drying. A mathematical model was used to determine the effect of drying temperature and relative humidity on the drying model constants and coefficients [1]. Ibrahim Doymaz (2007) [2] have conducted an experiment to study the drying characteristics of tomatoes at 55, 60, 65 and 70 °C with flow rate of 1.5m/s. The tomatoes were pretreated in alkaline ethyl oleate solution (2% ethyl oleate +4% potassium carbonate).Two drying models- Henderson and Pabis & Page models were used for the study and models were compared using reduced chi-square and coefficient of determination. The moisture content (w.b) was reduced from 94.5% to 11% and it was found that the pretreatment and air temperature affect the course and rate of drying. The activation energy of tomatoes was found to range from 17.40-32.94kJ/mol. Rajesh kumar et al. (2012) [3] have performed a computational fluid dynamics (CFD) model to calculate the unsteady, two-dimensional temperature, moisture and velocity distributions inside a novel, biomass fired, natural convection agricultural dryer. They have found that in the initial stage of drying, the MRR from the surface depends upon the condition of drying air and consequently when the surface of the material becomes dry, the MRR is driven by diffusion of moisture from inside to the surface. A nine-tray configuration was found to be effective in drying the materials than for the same mass of material and volume of dryer. A thermodynamic analysis of potato slice drying in a diagonal batch dryer was studied by Waseem Amjad et al. (2016) [4]. Exergy and Energy analyses were conducted on potato slices of 5mm and 8mm thickness at 55°C and 65°C. Fan-heater combination was found to be an important component in increasing the efficiency of the system. The energy utilization, exergy losses, energy utilization ratio and exergy efficiency ranged between 1.82 and 12.52kJ/s, 1.3 and 4.89kJ/kg, 0.04- 0.59 and 0.41-0.94, respectively for the potato slices. Romdhane Ben Slama and Michael Combarnous (2011) [5] have conducted a study on the development of forced convection solar dryer and kinetics of orange peel drying. They have found that addition of baffles in the mobile air vein have increased the effectiveness of solar collectors (efficiency reaches upto 80%). In addition to the correlations of temperature and air velocity in the drying rate of samples, they have further added that the drying rate also depends on the sectioning of the product to dry (surface area of contact with drying air). The moisture content of the samples was reduced from 76% to 13% in one day and the efficiency of the dryer was found to be 28%. Grape, copra, red chilli, banana and various other agricultural commodities were studied and reviewed. It was cited that solar drying can provide the demand for healthy, low cost natural foods and need for sustainable income. Solar dryers were known to save time, energy, less occupational area etc. for preservation of food and other agricultural produce. Compared to open sun drying, various models of solar dryer provide high quality products [6-10].

Forced convective solar drying is used for drying ghost chilli pepper and the result is compared with open sun drying. The moisture content of the sample was reduced from 589.6% to final moisture content of 12% (dry basis) in 123hrs and 193hrs for solar tunnel dryer and open sun drying respectively [11]. Solar tunnel dryer was used for drying pepper mint plants and the dryer performance was evaluated. It was observed that peppermint drying as leaves rather than the whole plant reduces the drying time while achieving highest volatile oil percentage. Drying rate of 24.8% (peppermint leaves) and 22.78% (peppermint plant) was obtained while drying with air flow rate of 2.10 m^3/min, loading rate of 4 kg/m^2 and continuous operation of the fan [12].

Crushed palm fronds drying was performed on a solar assisted solid desiccant dryer. A solar collector collects heat energy to heat up water and convective heat transfer was made to the surrounding air using two heat exchangers. The heated air increases drying air temperature after dehumidification. A desiccant wheel was used to improve air quality with sensible and latent effectiveness of 74% and 67% respectively. The improved solar dryer reduces the drying time by 64%, 44% and 33% for the products in the 1^{st}, 2^{nd} and 3^{rd} column of the dryer respectively. Rate of drying at full capacity using the dryer (8.37kg/hr) was twice than open sun drying (4.23kg/hr) [13]. Performance characteristics of a new design solar dryer were conducted for drying osmotically dehydrated cherry tomatoes. The dryer consists of drying cabinet, heat exchanger, water type solar collector and heat storage unit. It was observed that the efficiency of the solar dryer ranged from 21 to 69% for three batches of drying. The payback period was calculated to be 1.387 years [14]. Mixed mode solar dryer was used for drying fresh apricot slices and the overall thermal efficiency of the dryer was estimated to be around 11% [15]. A hybrid mixed mode solar dryer with integrated photovoltaic thermal solar air collectors was taken for thermal modeling for various parameters like crop temperature, greenhouse temperature, outlet air temperature etc. Commercial simulation tools such as MATLAB 2013a, CFD were used for the numerical study of drying characteristics for the solar dryer [16-17]. Solar dryer with thermal storage materials were used for drying of *Vitis vinifera* and *Momordica charantia* and the results have shown that sand as thermal storage material were effective in reducing the moisture content of the samples [18]. Solar dryer can also be used for drying various other materials such as ceramic, white mulberry, plaster molds using various parameters like indoor indirect type, mixed mode continuous type etc. [19-21].

The present investigation focused on convective drying of two (2) varieties of *Solanum lycopersicum* (Local and Hybrid) using a solar tunnel dryer. *Solanum lycopersicum* were chosen for the study since it is an important perishable food item which can be easily decayed by the action of the microbes. Other traditional food preservation methods were found to be less suitable in preserving *Solanum lycopersicum*, and hence solar drying is chosen as the best alternative for preservation. CFD was used as a tool to validate the temperature distribution along the mid plane of the dryer.

MATERIALS AND METHODS

Solar tunnel dryer

The experiments were conducted under the meteorological conditions of Negamam, Pollachi, India (*10.7426° N Latitude and 77.1032° E Longitude*) in the month of January & February (2017), with dimensions of 5000mm x 2500mm x 2500mm as length, width and height of the dryer, under full load conditions. The maximum RH of the STD was found to close by 30%. Using the necessary data recording devices, the maximum temperature inside the STD was found to be 63°C. A polyethylene ultra violet sheet of 200 micron is used for the study. Vents were provided on top of the dryer to facilitate the escape of moisture from the samples. The dryer is positioned in the E-W direction.

Two varieties (local/cultivated and hybrid) of *Solanum lycopersicum* were procured from the market. The samples were washed and no pretreatment was done on it. The samples were sliced in half so as to facilitate enhanced heat transfer rate. 30kg each of the local (cultivated) and hybrid samples were taken, in which 25kg each of the two varieties were loaded into the dryer. 5kg of each of the samples were taken for the open sun drying study purpose. The incident average solar radiation was found range from 476-790 W/m^2. Sunshine duration was recorded to be 11hrs and the drying period was 18hrs. The loading capacity of the dryer is 50Kg and the experiment is performed on full loading condition. Fig. 1. indicates the loading of samples (a) cultivated and (b) hybrid varieties of *Solanum lycopersicum* in the STD.

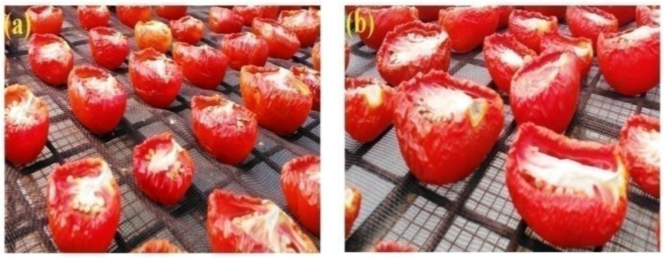

Figure 1. Loading of samples (*Solanum lycopersicum)* in the STD [(a) cultivated, (b) hybrid]

Instrumentation

A data acquisition system of SIMEX (SRD-99) is used for the experiment of uncertainty ±0.25%. RIXEN TRH-303W is used for measuring humidity (0-100%) and temperature (0-100°C) with uncertainty ±1%. A pyranometer from Delta Ohm of range 0-2000 W/m^2 with an uncertainty ±5% was employed during the course of the experiment. An uncertainty analysis was conducted and the overall uncertainty from the desired parameters were 2.4, 2.7, 3.8 and 3.2 for moisture removal rate,

rate of drying, drying efficiency and moisture content of the samples.

Data analysis

The following are the considerations made during the experimentation to calculate the corresponding moisture removal rate, rate of removal of weight and dryer efficiency etc. as given in the equations (1), (2) and (3) respectively. The moisture content of the samples (wet basis) was expressed in terms of percentage (%). This is done using an electric oven (convective) with a temperature of 105±5 °C. The weights of the samples (initial and final) were recorded using an electric weighing machine. Five (5) cycles of drying were taken for both the solar tunnel dryer and open sun drying through which an optimal cycle was selected and the results are discussed herein this paper.

$$M_{wb} = \frac{m_i - m_f}{m_i} \times 100 \qquad (1)$$

$$m_w = \frac{W_{in} - W_{out}}{100 - W_{out}} \qquad (2)$$

$$\eta_{th} = \frac{m_w \times h_{fg}}{A \times I} \times 100 \qquad (3)$$

RESULTS AND DISCUSSION

The experiments were conducted for five cycles and the most optimum cycle is taken for the discussion of the result. The experimental and computational validations are discussed below. The rate of moisture removal (w.b.) was taken for evaluating the performance of the solar tunnel dryer for drying the samples. Initially, 100gm of the sample was taken out for use in a convective oven to determine the moisture content of the sample (w.b.). The mass flow rate of air was found to be 7.65 ± 0.0017 Kg/s corresponding to velocity 0.5 ± 0.2 m/s. Table 1 shows the performance indices for the solar tunnel dryer.

Table 1. Standard deviation and mean of the performance indices for the solar tunnel dryer

Parameters	Unit	Mean ± SD
Rate of heat added to the ambient	kW	186.49 ± 9.6
Heat loss to the ambient	%	24.97 ± 5.45
Thermal efficiency	%	20.4 ± 1.6

MRR and time

Moisture removal rate is the rate of evaporation of water vapor (moisture) from the samples. The MRR during drying signifies the capability of the system to remove vapor from the samples. The rate of moisture removal with respect to the time is shown in the fig. 4. From the graph plotted, it can be seen clearly that the moisture content of the samples in the tunnel dryer were removed significantly, as compared with the open sun drying. The initial moisture content was found to be 91.50% and it was reduced to 4.001% in 31hrs (cultivated, TD), 4.266% in 27hrs (hybrid, TD), 5.35% in 29hrs (cultivated, OD) and 9.86% in 48hrs (hybrid, OD). The two stages of constant phase (8th to 23rd hrs and 33rd hrs to 48th hrs) in the graph can be accounted to moisture re-absorption (1–2 %) in the samples during night.

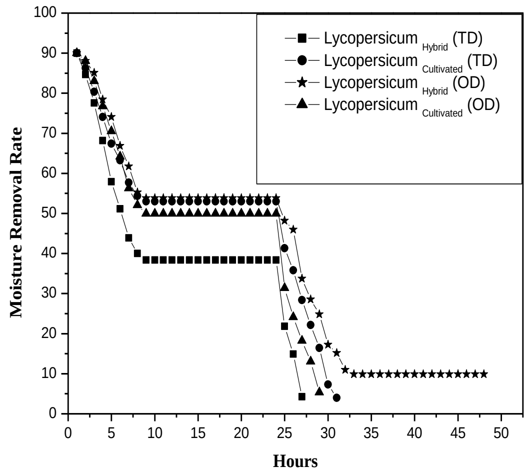

Figure 4. MRR variation with time

Weight removal rate and time

The removal of weight of the samples (grams) in a day 10:00-17:00 hrs is plotted in fig. 5 for both the varieties of the sample in solar tunnel dryer as well as open sun drying. In respect to weight removal rate, cultivated variety in STD have reduced from 106gms to 75.5gms, hybrid variety in STD have reduced from 103.5gms to 60.5gms. While in open sun drying, the cultivated variety have reduced from 103gms to 71gms and the hybrid variety have reduced from 102gms to 67.5gms. The halt in the reduction of weight of the samples after 17:00hr is due to absence of heat (solar) application on the samples. After 27-47hrs of drying of the samples, the final reductions in weight of the samples were: (STD, cultivated-57.5gms), (STD, hybrid -25.5gms), (OSD, cultivated - 45gms) and (OSD, hybrid - 30.5gms)

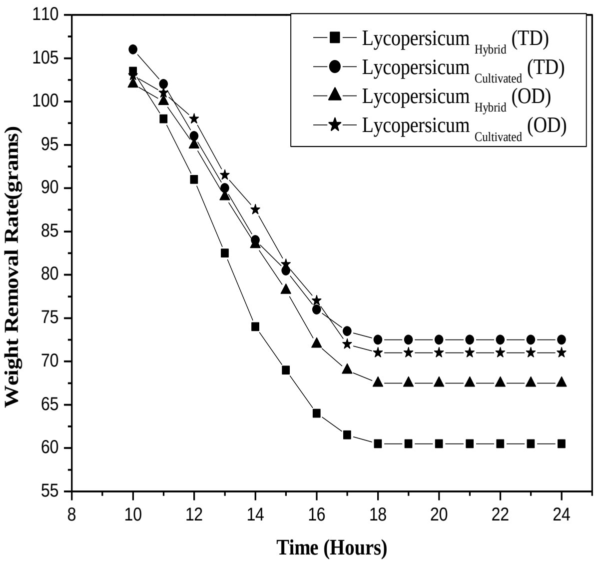

Figure 5. Weight removal rate with time

Relative humidity and time

Relative humidity is the amount of water vapor present in the air. It is desired that the RH of the air should be as low as possible to facilitate higher drying capability of the air. Fig. 6 shows the RH inside the dryer and the ambient air. The RH of the air is expressed in terms of percentage. It was found that the RH of air in the dryer varied from 35% to 42% and that of the ambient varied from 46% to 44.6%. Thus the dryer air has significant drying potential as compared with ambient air.

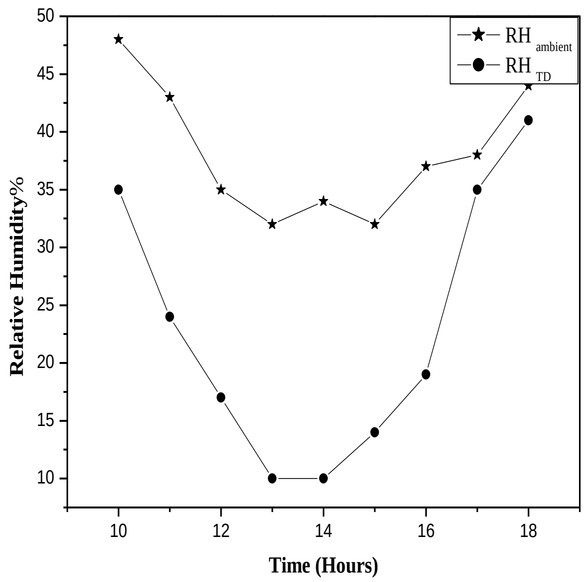

Figure 6. Variation of RH with time

Drying efficiency and time

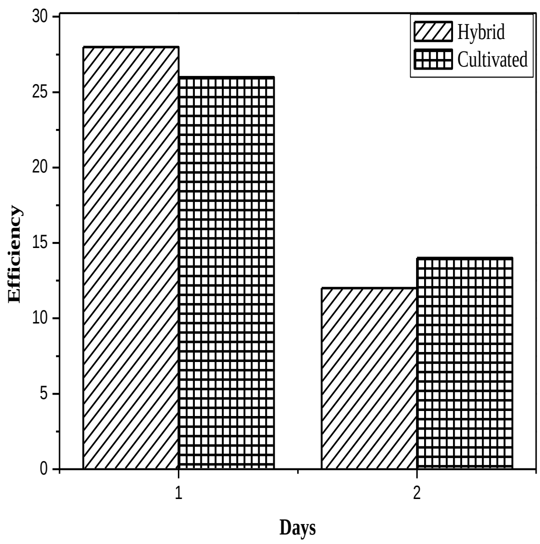

Figure 7. Efficiency of solar tunnel dryer with time (days)

The efficiency of the solar tunnel dryer for drying of the samples was plotted in the fig. 7. It can be observed that the efficiency of the dryer was more while drying the hybrid samples in the first day and get reduced on the corresponding day. The average thermal efficiency of the dryer was closing to around 20.4%.

Validation

The computational model was generated using ANSYS 15 to validate the experimental results which were obtained from the dryer. The surface-to-surface radiation model can be used to account for the radiation exchange in an enclosure of gray-diffuse surfaces. The energy exchange between two surfaces depends in part on their size, separation distance, and orientation. The main assumption of the S2S model is that any absorption, emission or scattering of radiation by the medium is ignored. Therefore only S2S radiation is considered for analysis. The total number of cells, faces and nodes are 87761, 258245 & 81787 respectively. The following equations (4) and (5) are used as governing equations for solving the problem.

$$q_{out,k} = \varepsilon_k \sigma T_k^4 + \rho k q_{in,k} \tag{4}$$

$$A_k q_{in,k} = \sum_{j=1}^{N} A_j q_{out,j} F_{jk} \tag{5}$$

The computational model is analyzed on the mid line of the dryer taking along the Y-axis (along the height of the dryer). It was found that the temperature distribution of the solar tunnel dryer in the mid line from the experiment comes very close to the predicted temperature distribution curve along the same line. The graph plotted in the fig. 8 shows the closeness of the predicted and experimental value of the temperature distribution about the mid line in the Y-axis.

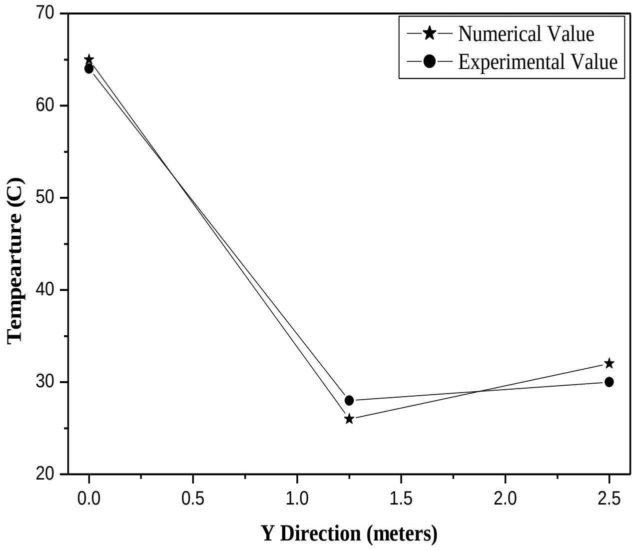

Figure 8. Validation of experiment model using computational analysis

Solanum lycopersicum after drying

The fig. 9 & 10 shows the samples after drying in the solar tunnel dryer and open sun drying for both varieties of the product. In fig. 9, the cultivated varieties (a) were found to have more water content than the hybrid variety (b) obtained from the same tunnel dryer. The same can also be noted on the dried samples from the open sun drying as shown in the fig. 10 (a) and (b).

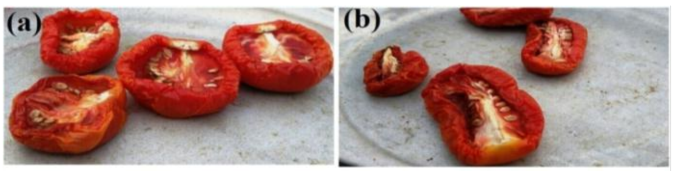

Figure 9. *Solanum lycopersicum* in solar tunnel dryer [(a) cultivated, (b) hybrid]

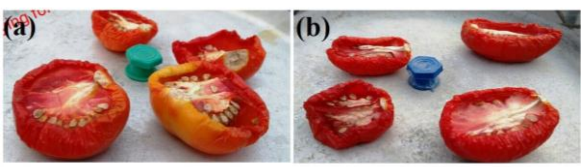

Figure 10. *Solanum lycopersicum* in open sun drying [(a) cultivated, (b) hybrid]

CONCLUSION

Solar tunnel dryer is used for drying samples of *Solanum lycopersicum* which were procured from the local market of Pollachi, Tamilnadu, India and open sun drying is used to verify the effectiveness of the solar tunnel dryer. The following conclusions are made based on the study. The samples from the STD yields better shelf life and quality as compared to the samples from the open sun drying.

- The solar dryer works efficiently by reducing the moisture content of *Solanum lycopersicum* from 91.50% to the desired 4.001% in 31hrs (cultivated) and 4.266% in 27hrs (hybrid). The open dun drying reduces the moisture content of the samples to 5.35% in 29hrs (cultivated) and 9.86% in 48hrs (hybrid).
- Significant weight reduction occurs in the hybrid variety of the sample in the dryer, 103.5gms to 25.54gms during 10:00 hrs to 17:00 hrs. Relative humidity of the air inside the dryer was found to be lower by 11% to 5% as compared with ambient air. The average thermal efficiency of the dryer while drying the sample was found to be 20.4%
- The results of the simplified model were compared with radiation surface to surface (S2S) model of a detailed and experimentally validated 3-D computational fluid dynamics model. It shows the proximity of the predicted and experimental value of the temperature distribution about the mid plane in the Y-axis of the STD. Hence there is a good agreement between the results.

NOMENCLATURE

A	: area of the surface (m^2)
CFD	: computational fluid dynamics
F_{jk}	: view factor
h_{fg}	: enthalpy (J/kg K)
I	: incident solar radiation (W/m^2)
m	: mass (kg)
MRR	: moisture removal rate (grams)
M_{wb}	: moisture content of product (%)
$q_{out,k}$	: energy flux leaving the surface (W/m^2)
$q_{in,k}$	: energy flux incident on the surface from the surrounding (W/m^2)
RH	: relative humidity (%)
SD	: standard deviation
STD	: solar tunnel dryer
S2S	: surface-to-surface model
T	: temperature (K)
UV	: ultraviolet

η_{th} : thermal efficiency (effectiveness)

ε : emissivity (W/m^2)

σ : Stefan Boltzmann's constant ($W/m^2\ K^4$)

ρ : density (kg/m^3)

f : final

i : initial

j : incident surface

k : surface

in : inlet

OD : open sun drying

out : outlet

TD : solar tunnel drying

w : water

wb : wet basis

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