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Experimental and Theoretical Study of Thompson Seedless Grapes Drying using Solar Evacuated Tube Collector with Force Convection Method

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ABSTRACT

An evacuated tube solar collector drier is designed and developed to study analytically and experimentally drying kinetics of Thompson seedless grapes in Pune, India. Drying experiments are carried out in the month of April- June for continuous three years from 2013-2015. During the experimentation, temperatures of hot and cold air at various places, ambient relative humidity and humidity variation in drying chamber, wind velocity and mass of the grape are measured on hourly basis. 10 kg of Thompson seedless grapes are dried in forced convection heat transfer mode from initial moisture content of 76% (wb) to final moisture content of 15%(wb) in 37 hours. The drying is carried out under the uncontrolled conditions. The average evacuated tube solar collector efficiency is found to be 24.5% whereas the stacked type dryer which is insulated from outside has given drying efficiency up to 37.1%. To study drying behavior analytically nine different drying models have been tested. It is observed that, Page model describes the drying behavior accurately with highest coefficient of determination (R^2 = 0.993), lowest reduced chi-square ($\chi 2 = 5.19 \times 10^{-5}$) and lowest root mean square error (RMSE = 0.02071).

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1. INTRODUCTION

Reducing the moisture content by drying the vegetables and fruits is one of the oldest forms of agricultural product preservation methods. It is the most important process to preserve food material as it has lot of influences on the quality of the dried products. The major objective in drying agricultural products is the reduction of the moisture content to a level called as equilibrium moisture content, which allows safe storage over an extended period. Moisture removal from food products prevents the growth and reproduction of microorganisms which cause decay [1]. Drying the grapes and making raisins form different types of grapes has good economic value. Drying technique has lots of impact on quality of product. The most common drying method is sun drying, which is traditionally practiced in many countries [2]. This traditional method has the advantages of simplicity and less initial investment. However, it requires large areas, high labour costs and the drying process completes in 15–20 days which is uneconomical [3]. In order to improve the quality, traditional sun drying techniques can be replaced by industrial drying methods such as hot-air mechanical and solar drying [4]. It is reported in the past literature that investigation on solar and hot-air drying of agriculture food products have been carried out by many researchers [5-10]. The drying kinetics of grapes undergoing solar drying with various pre-treatments was also investigated [11].

To overcome the limitations of natural sun drying, many researchers have proposed new mechanical types of driers in the recent years. Many of them are rather working on electricity or fossil fuel and the energy reserves are depleting at a rapid rate. These systems cause pollution. Solar energy is abundantly available and is also inexhaustible. Mechanical driers which use sun as the source of energy can solve the problem [12].

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In the present study, the main objective is to design and fabricate a novel solar drier using ETC and studying its performance. Drying kinetics of Thompson seedless grapes are evaluated experimentally in Symbiosis Institute of Technology campus, Pune (India). The best suitable mathematical model is selected analytically to describe the drying behavior of grapes.

2. MATERIAL AND METHOD

2. 1. Experimental Set-up As shown in figure 1, solar collector is formed by arranging ten evacuated tubes with the dimensions as; 55 mm diameter and 1800 mm length. The array of tubes is inclined 45^0 to horizontal on steel frame. At any instant the collector exposed area to direct sun light is measured as 1.618 m^2. The point of contact of the evacuated tube to frame is insulated with polyethylene foam sheet with thermal conductivity of 0.04 w/m k to minimize the heat loss. The output of all tubes is collected and supplied to the dryer chamber from a 60 mm diameter pipe. Forced air is provided by 12 V/1A five fans which run on the 15 watt solar panel. Dryer chamber is designed on the criteria of collector surface to volume of dryer ratio i.e. $R = \frac{SA}{V} > 3$ which is found as 4.4 [13]. The dryer chamber is made up of 0.6 mm thick aluminum alloy sheet. On the bottom and top of rectangular chamber, divergent and convergent sections are made to observe uniform flow of the hot air. To minimize the heat loss from the dryer chamber to surrounding, it is insulated with 12 mm polyethylene foam sheet. The drying chamber consists of three stainless steel mesh trays to load the grapes.

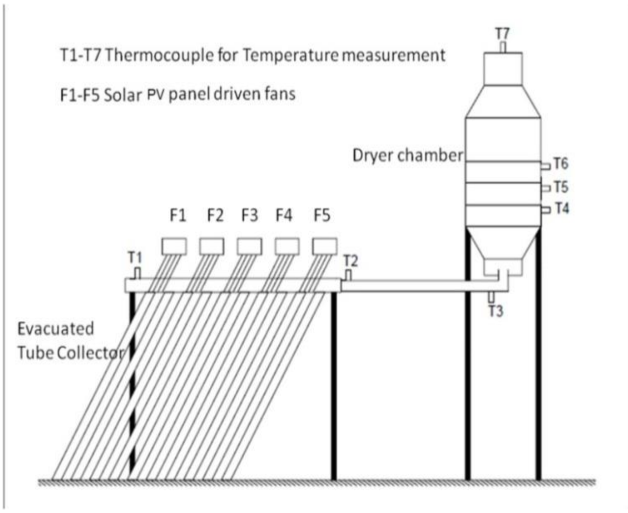

Figure 1. Schematic view of ETC solar dryer

Figure 2. Pictorial view of ETC and solar dryer

2. 2 Measuring Instruments and Devices Diurnal variation of the relative humidity, ambient temperature and air temperature on each tray of dryer is monitored on every hour basis for test time. Sample bunches from each tray are weighted after every hour with an electronic weight balance of accuracy ± 1grams from morning 9 am to evening 6 pm [14, 15]. RTD Pt-100 sensors (accuracy ± 0.1°C) with microcontroller reading facility and 12 channel selector switch are used to record the temperature. Various temperatures like ambient condition, air outlet to collector and inlet to dryer chamber are recorded. Two thermocouple sensors are put up on each tray of dryer chamber. Also dryer outlet temperature is monitored per hour. Air velocity is measured for all reading with anemometer (accuracy 0.1m/s) in dryer and at the exit of dryer. Solar radiation is measured with the help of solar pyranometer having the accuracy ±3%. All the equipments are branded equipments and are calibrated with standard calibrating agency.

2. 3. Experimental Procedure The initial moisture content of Thompson seedless grapes is determined by oven drying method. To maintain similar physical properties of test samples, grapes from same lot are selected for experimentation as well as for moisture determination. 10 kg of fresh Thompson seedless grapes are selected and sorted for infected berries. These are washed with tap water to remove dirt and dust. Conventional alkaline pre-treatment is done to increase the water permeability. Deeping oil (2.5%) and Na_2CO_3 (2%) are used as agents [14-16]. Grapes bunches are dipped for two minutes and equally spread on the three trays in dryer chamber made up of stainless steel mesh. Experiments are carried out from morning 9 am to evening 6 pm.

2. 4. Experimental Uncertainties The collected data consist of several uncertainty sources during measurements such as solar radiation measurement, temperature measurement at various locations in collector and dryer, air velocity, relative humidity, current and voltage measurements, etc. In current experimentation, it is assumed that there is negligible heat loss from dryer chamber to the surrounding. Further the heat losses due to convection and radiation from evacuated tubes are considerably very small, hence are not calculated separately. The pressure drop of the working fluid in the collector is also not considered as the air velocity is measured at inlet and out let of dryer. Successive measurements under identical operating conditions give different results with small change. This variation is of the order of 2–5% which is acceptable.

2. 5. Drying Kinetics If M_p is total mass of grapes to be dried from initial moisture content M_i to final moisture content M_f on wet basis then mass of water M_w to be evaporated from the grapes, is given by [13, 17]:

TABLE 1. Uncertainties in the measurements

Parameter	Unit	Accuracy (%)
Solar radiation measurement	W/m^2	$\pm$1 to 2
Ambient temperature	^0C	$\pm$0.3
Collector outlet temperature	^0C	$\pm$0.3
Drying chamber inlet temperature	^0C	$\pm$0.3
Drying chamber outlet temperature	^0C	$\pm$0.3
Mass loss values	min	$\pm$0.1
Uncertainties in air velocity measurements	m/s	$\pm$0.15
Uncertainties in mass flow measurements	kg/s	$\pm$0.005
Uncertainties in relative humidity measurements	RH	$\pm$0.1
Uncertainties in moisture quantity measurements	kg	$\pm$0.0001
Uncertainties in reading the standard values like C_p, ρ etc.	%	$\pm$0.2

$$\dot{M}_w = \frac{M_p(M_i - M_f)}{100 - M_f}\ (Kg) \tag{1}$$

The non dimensional parameter moisture ratio (*MR*) is calculated as [6, 16, 18, 19]:

$$\dot{M}R = \frac{(M_i - M_e)}{(M_t - M_e)} \tag{2}$$

where, M_t and M_e are moisture content at any time, and equilibrium moisture content, respectively. The equilibrium moisture content of the grapes is calculated by well known Guggenheim-Anderson-de Boer (GAB) equation. To complete the system of equations, an appropriate thin layer equation is normally employed [16, 20].

Various mathematical models which are extensively suitable for drying of high moisture content food product such as grapes are listed in Table 2. In these equations, *t* is the drying time and *k*, k_0, k_1, *n*, *a*, *b*, *c*, *g* and *h* are the drying equation constants. Various experiments are carried out and non dimensional moisture ratio (*MR*) is found out using Equation (2). Custom made programs in MATLAB14B software is used to find out the different constants of the equations.

The equations used to predict correlation of coefficient (R^2), reduced chi-square (χ2) and root mean square error (RMSE) are as follows [10, 18, 19, 21, 22]:

$$\dot{R}^2 = \frac{\{\sum_{i=1}^{n}(\mathrm{MR}i - \mathrm{MR}exp,i)(\mathrm{MR}i - \mathrm{MR}pre,i)\}}{\sqrt{\{\sum_{i=1}^{n}(\mathrm{MR}i - \mathrm{MR}exp,i)^2 \sum_{i=1}^{n}(\mathrm{MR}i - \mathrm{MR}pre,i)^2\}}} \tag{3}$$

$$\chi 2 = \frac{\{\sum_{i=1}^{n}(\mathrm{MRexp}i - \mathrm{MR}pre,i)^2}{N - n} \tag{4}$$

$$RSME = \frac{1}{N}\{\sqrt{\sum_{i=1}^{n}}(\mathrm{MRexp}i - \mathrm{MR}pre,i)^2\} \tag{5}$$

where, *MRi* is the i[th] experimental moisture ratio, and *MRpre,i* and *MRexp,i* are the mean of sum of MR respectively, *N* is total number of observations and *n* is number of constants in the equation, respectively. The model that has highest correlation coefficient (R^2), lowest reduced chi-square (χ^2) and lowest root mean square error (RMSE) value is considered as the most accurate model for drying [10, 18, 19, 21-24]. The efficiency of the drier is given by [25]:

$$\dot{\eta} = \frac{Lw\sum Mw}{3600\sum I_G(t)A_C} X100 \tag{6}$$

where Lw is latent heat of water, Mw represents total mass of water which has to be removed in time *t*, I_G is the total hourly solar radiation falling on tilted surface of the collector and A_C is the effective area of the solar collector.

Instantaneous ETC thermal efficiency is calculated using following equation:

$$\eta_{Coll-Th} = \frac{Q_u}{A_C * I_G} * 100 \tag{7}$$

where Q_u is heat gain by working fluid in Watts.

2. 6. Mathematical Models for Drying Grapes

Based on the past literature, the following mathematical models are selected for analysis purpose, which describe drying behavior of food products with high moisture content.

TABLE 2. Mathematical models for drying of food products

Mathematical model	Equation	Reference
Newton	$MR = e^{-kt}$	[6,8,19, 22-27]
Page	$MR = exp(-kt^n)$	[6, 19, 22-27]
Henderson & Pabis	$MR = a.e^{-kt}$	[6, 19, 22-27]
Logarithmic	$MR = a.e^{-kt} + c$	[6,8,19, 22-25]
Two term	$MR = a.e^{-kot} + b.e^{-k1t}$	[6,14,22-25, 27]
Two term exponential	$MR = ae^{-kt} + (1-a)\, e^{-kat}$	[6, 22-25, 27]
Wang & Singh	$MR = 1 + at + bt^2$	[8,19,22-25,27],
Diffusion approach	$MR = a.e^{-kt} + (1-a)e^{-kbt}$	[8,18,22-25, 27]
Modified Henderson & Pabis	$MR = a.e^{-kt} + b.e^{-gt} + c.e^{-ht}$	[8,14,22-25, 27]

3. RESULTS AND DISCUSSION

Experiments are conducted in the month of April- June for continuous three years from 2013 to 2015 at the Symbiosis Institute of Technology, Pune campus with geographical data as, 18.5203° N, 73.8567° E. Table 3 shows the experimental data for the sample test day. Various parameters like solar radiation, temperature and relative humidity of ambient, collector and dryer are recorded per hour, from morning 9 am to evening 6 pm for all tests. The air velocity at the inlet of dryer is observed in the range of 2.1 to $2.7 m/s$. Mass flow rate, heat gained by the air and instantaneous collector efficiencies are calculated as shown in Table 3. In the month of May the solar radiation and temperature goes high but efforts are made to start dryer system operative early, in the month of April when solar radiation is considerably less in the test region. This way more time will be available so it will reduce the requirement of higher capacity dryers for same amount of the raisins production.

3. 1. Mathematical Modeling

Constants, k and n of all nine mathematical models are calculated by using experimental and analytical method and shown in Table 4 for two sample tests readings. By comparing all the models which gives highest R^2, lowest reduced $\chi 2$ and lowest RMSE is considered as best describing model. This comparison is shown in Table 5. It is observed that Page's model describe accurately drying of Thompson seedless grapes with coefficient of determination value R^2=0.993, reduced $\chi 2 = 5.19 \times 10^{-5}$ and RMSE = 0.02071.

TABLE 3. Solar radiation, temp, relative humidity, mass flow, heat gain and thermal efficiency for typical test day

Time	Solar radiation	Ambient		Collector out Temp.	Velocity of air m/s	Mass of air kg/s	Heat gain in J/s	ETC thermal efficiency
	in W/m^2	Temp	% RH					
9	411	23.4	32	28.5	2.5	0.013226	67.85567	10.31869
10	649	30.8	25	44.3	2.4	0.012887	175.0124	16.85404
11	812	31.6	22	51.3	2.5	0.013226	262.1092	20.17466
12	848	32.5	21	61.3	2.7	0.013565	393.0102	28.96597
13	919	34.5	21	67.8	2.5	0.013226	443.0576	30.13178
14	851	35.8	19	67.9	2.5	0.013226	427.0916	31.36689
15	715	34.8	22	59.3	2.4	0.012887	317.615	27.76355
16	535	32.8	25	51.1	2.5	0.013226	243.4821	28.44417
17	465	29.8	28	44.3	2.4	0.012887	187.9763	25.26563
18	321	25.6	31	38.1	2.3	0.012547	157.7841	30.7212

TABLE 4. Values of model constants

Model name	***Model constants for Set I***	***Model constants for Set II***
Newton	*k*= 0.04459	*k*=0.04038
Page	*k*=0.02756 *n*=1.161	*k*=0.03074 *n*=1.09
Henderson and Pabies	*a*=1.052 *k*=0.04755	*a*=1.032 *k*=0.04217
Logarithmic	*a*=1.117 *k*=0.04128 *c*=-0.07868	*a*=1.038 *k*=-0.006966 *c*=0.04163
Two term	*a*=-0.06471 *b*=1.065 k_0=20.59 k_1=0.0483	*a*=1.068 *b*=-0.06991 k_0=0.04396 k_1=0.3477
Two-term exponential	*a*=1.708 *k*=0.06196	*a*=0.8546 *k*=0.0435
Wang and Sing	*a*= -0.03823 *b*=0.0004343	*a*=-0.03629 *b*=0.00042
Diffusion approach	*a*=-0.1465 *b*= 0.1936 *k*=0.2684	*a*=-0.06821 *b*=0.1276 *k*=0.3443
Modified Henderson & Pabies	*a*=13.64 *b*=-12.92 *c*= 0.5395 *k*=0.03381 *g*=0.03406 *h*=0.2727	*a*=1.71 *b*=-0.9182 *c*=0.8023 *k*= 0.02747 *g*=0.02666 *h*=0.9161

TABLE 5. Values of sttistical analysis

Model Name	R^2	$\chi 2$	***RMSE***
Newton	0.9853	0.001027	*0.03125*
Page	**0.993**	**5.19162e-05**	**0.02071**
Henderson & Pabies	0.987	4.29772e-05	0.0221
Logarithmic	0.989	1.13128e-07	0.02393
Two term	0.9783	0.007111	0.02356
Two-term exponential	0.9665	0.001356	0.06098
Wang and Sing	0.9826	0.000563	0.02251
Diffusion approach	0.9847	3.94521e-04	0.0192
Modified Henderson & Pabies	0.9003	0.004435	0.1875

The values of model constants are in the range of *k*=0.02645 to 0.0312 and *n*=1.17 to 1.087.

Figure 3 shows experimental dimensionless drying parameter MR plotted against the drying time *t*. Figure 4 is showing the comparison of the experimental and Page's model non dimensional MR with respect to drying time. It is observed that predicted and experimental values fit at almost all the points. Hence it is evident that Page model is the most accurate model to describe the drying kinetics of Thompson Seedless grapes.

Figure 5 shows comparison of all the nine mathematical models and actual moisture ratio with respect to time. Whereas, Figure 6 describes the experimental and predicted MR values, with coefficient of determination as 0.993.

The maximum solar collector thermal efficiency is observed as high as 31% and the average value is 24.5%, which is more than the flat plate type of solar collector [16, 24]. The value of drying efficiency is found to be more during morning hours than afternoon hours due to increase in drying air temperature inside the chamber which results in increase in moisture loss. The drying efficiency is found up to 37.1%, with designed solar drying system.

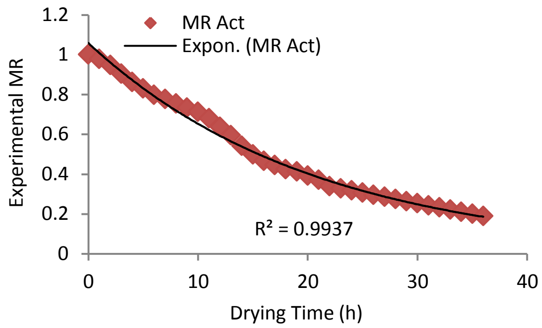

Figure 3. Moisture Ratio (MR) *vs* drying time

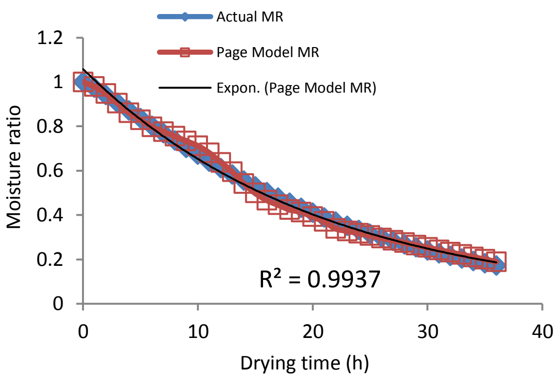

Figure 4. MR act and MR Page *vs* drying time

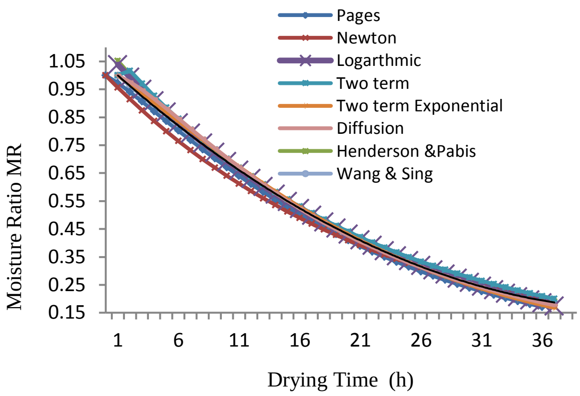

Figure 5. Comparison of all mathematical model's MR values *vs* drying time

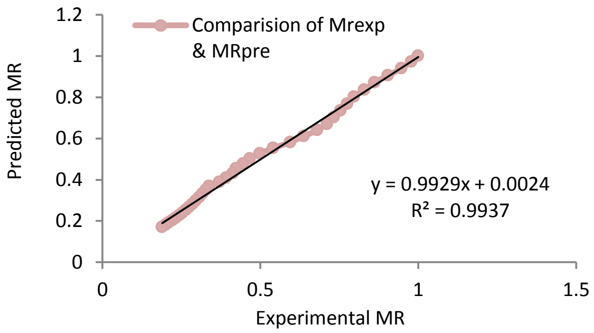

Figure 6. Experimental *vs* predicted MR values of Page model

4. CONCLUSION

An ETC solar dryer is designed, fabricated and tested. Drying kinetics of Thompson seedless grapes is evaluated experimentally as well as analytically. Thompson seedless grapes are dried in forced convection heat transfer mode from initial moisture content of 76% (wb) to final moisture content 15% (wb) in 37 hours. The quality of the grapes is observed to be better than traditionally dried grapes with good market acceptance value. The drying is carried out under the uncontrolled conditions of environment. The average evacuated tube solar collector efficiency is found 24.5% whereas drying efficiency is observed 37.1%. To study drying behavior analytically, various drying models have been tested. It is observed that, Page model describes the drying behavior accurately with highest coefficient of determination (R^2 = 0.993), lowest reduced chi-square (χ^2 = 5.19x10^{-5}) and lowest root mean square error (RMSE = 0.02071) and the values of drying constants are k=0.02756 and n=1.161.

The designed dryer system works on renewable source of energy with zero emission. The drier can be also used to dry other types of agriculture products.

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Forced Convection

چکیده

یک خشک کن کلکتور خورشیدی لوله توخالی طراحی و توسعه یافت و مطالعه تحلیلی و تجربی سینتیک خشک کردن انگور تامپسون بیدانه در پونا، هند، انجام گرفت. آزمایش های خشک کردن در ماه آوریل- ژوئن در سه سال متوالی از ۲۰۱۳ تا ۲۰۱۵ انجام شده است. در طول آزمایش، دمای هوای سرد و گرم در مکان های مختلف، رطوبت نسبی محیط و تنوع رطوبت در محفظه خشک کن، سرعت باد و وزن انگور به صورت ساعتی اندازه گیری شد. ۱۰ کیلوگرم انگور تامپسون بیدانه در حالت انتقال حرارت همرفت اجباری از رطوبت اولیه ۷۶٪ (وزنی) تا رطوبت نهایی ۱۵٪ (وزنی) در ۳۷ ساعت خشک شد. فرایند خشک کردن تحت شرایط کنترل نشده انجام شد. متوسط راندمان کلکتور خورشیدی لوله توخالی ۲٤/۵درصد بود در حالی که خشک کن انباشته که از خارج عایق شده بود بهره وری خشک کردن تا ۳۷/۱ درصد داشت. برای مطالعه رفتار خشک کردن به صورت تحلیلی، نه مدل مختلف خشک کردن آزمایش شد. مشاهده شد که مدل پیج با بالاترین دقت ضریب تعیین (R^2 = 0.993)، کمترین کاهش مجذور کای (χ^2 = 5.19x10-5) و کمترین ریشه میانگین مربعات خطا (RMSE = 0.02071) رفتار خشک کردن را توصیف می کند.

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