Comparative Drying Performance Study of Natural Convection Solar Dryer with Traditional Grape Drying Methods

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ABSTRACT

A natural convection solar dryer, a unit of agricultural produce processing system using solar energy as a renewable energy source for producing heat, was developed and tested. This natural convection solar dryer consists of solar air heater and drying chamber. In the developed natural convection solar dryer, Thompson seedless grapes were successfully dried. For quantitative analysis, the traditional (open sun and shade) drying tests were carried out. The result shows that the solar dryer reduces the drying time of grapes significantly and is most efficient and more effective. Sensory evaluation shows that the organoleptic qualities of raisins produced in solar dryer are of superior quality than those produced using traditional drying methods.

1. INTRODUCTION

Grapes are considered as the most perishable fruit in agricultural produce and have very short shelf as well as storage life. Grapes at 0°C have storage life of only 2 to 8 weeks [1], while raisins are reasonably stable when stored at 20°C. Lower storage temperature would give increased shelf life of about 12 months. The storage life of grapes can be increased by drying grapes in the form of raisins either by mechanical or traditional means (open sun or shade drying). Similarly by using proper drying techniques, post-harvest losses of grapes can be drastically reduced.

In open sun drying, grapes are spread on ground, where they are directly exposed to the sun and wind. Open sun drying method [2] produces low quality raisins and also results in considerable losses due to various influences such as rodents, birds, insects, and rain. In shade drying method [2], chemically pre-treated bunches of grapes are laid on the long narrow wire screen racks under the shelter of iron sheet roof which is generally slightly wider than stack of wire racks. The principal source of heat required is the ambient air. This method is also found to be unsatisfactory because of mass losses and low quality of raisins produced. It is very difficult or impossible to achieve drying without severe losses to quality and quantity. Hence mechanical dryers can be used for drying of grapes, but the limiting factors for using conventional mechanical dryers at small-scale or at farmers level in the developing countries are the initial cost and scarcity of energy. Therefore, solar dryer should be considered as an alternative to the traditional drying methods when higher quality products are desired. The initial additional cost involved in the installation of solar dryers can be recovered through increased profits obtained from the dried product (raisins) within about 1 to 3 years depending on the operating conditions or by drying economical products like grapes and onions, and utilizing the dryer for multiple use.

Various studies [2-5] have been made to develop different types of solar dryer for drying grapes. Though the quality of raisin produced in those dryers was good, most of them required electrical energy to circulate drying air. Hence it becomes necessary to develop a dryer capable of maintaining the quality of raisins without use of electrical energy and without running cost. In this present study, a new multi-purpose natural convection solar dryer was developed and tested for Thompson seedless grapes. For quantitative analysis of the solar dryer, traditional (open sun and shade) drying methods were also carried out simultaneously and the results of these drying methods in terms of organoleptic qualities and dryer efficiencies, along with their drying constants (k), are presented in this paper.

2. NATURAL CONVECTION SOLAR DRYER

The developed natural convection solar dryer [6, 7] consists of solar flat-plate air heater, flexible connector, reducer cum plenum chamber, drying chamber along with the trays and a supporting stand as shown in Fig. 1. The air duct of a solar air heater was made of 0.5 mm thick aluminium sheet of size 2.47 m x 0.73 m x 0.03 m through which air was allowed to pass and heated up. The top painted black surface of air duct of size 1.80 m x 0.73 m having U-shaped corrugations acted as an absorber surface for solar radiation. The air duct was covered with GI box of 1.90 m x 0.83 m overall size. To reduce the thermal losses, glass wool (5 cm thick) was placed between air duct and GI box as heat insulator. The toughened glass plate was fitted on top of rectangular GI box at a distance of 4 cm above the air duct. More detailed information about collector characteristics and its performance is available in previous study [7].

The drying chamber (0.35 m x 0.35 m x 0.70 m inside dimension) with inside wall made from 0.5 mm thick aluminium, was covered by GI sheet with glass wool (5 cm thick) placed in between them. The drying chamber had five aluminium trays having a wire mesh bottom. For loading and unloading of

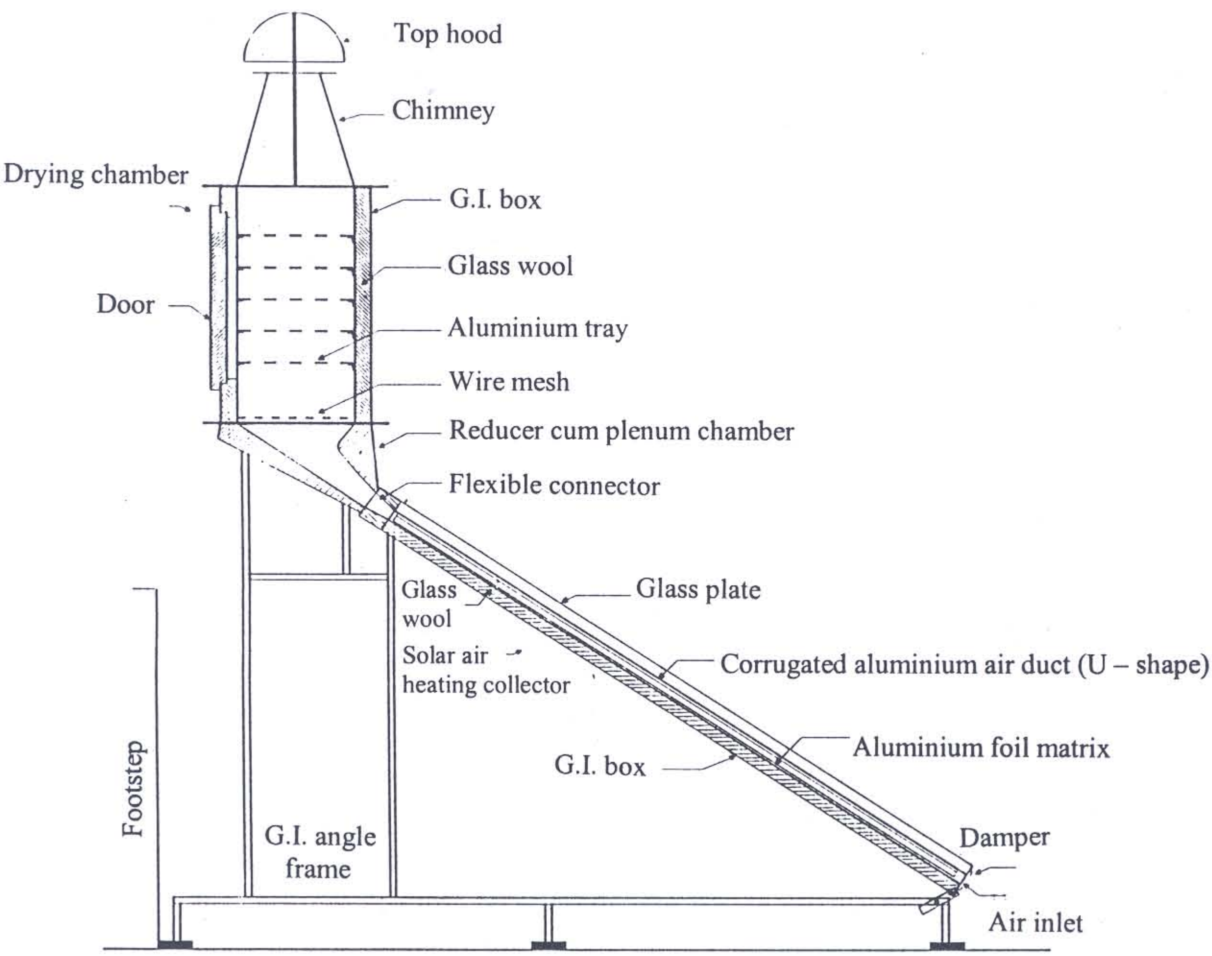

Fig. 1. Sectional details of natural convection solar dryer

grape trays, a door was provided at the rear part of the drying chamber. By providing a chimney at the top of drying chamber, the required draft through the dryer was created. The reducer with flexible connector was used to connect air duct of solar air heater to the drying chamber. The Pt-100 RTD (0.01°C) sensors (with and without wet wick) were fixed at various required places in the drying chamber and air heater, for measuring dry and wet bulb temperature along with the ambient temperature. For measuring the solar irradiance, a radiation pyranometer was placed in the plane of collector. Similarly for measuring weight loss of the grape sample, an electrical balance (0.0001g accuracy) was placed near the solar dryer.

3. EXPERIMENTATION AND ANALYSIS

The solar dryer and traditional (open sun and shade) drying experiments were performed for two cases. In the first case, bunches of grapes cut into small sub-bunches having three to four berries were dried. The sub-bunches of grapes were uniformly spread on five trays of the solar dryer and simultaneously on aluminium wire mesh trays, for open sun and shade drying. In the second case, full grape bunches as available from grapevine were dried. The full bunches of grapes were hanged from rods which were placed at the center of the drying chamber after removal of all trays. The other grape bunches were hanged in the open sun and under the shade for drying.

The drying tests were carried out with manually harvested fresh Thompson seedless grapes. The drying process of grapes involves various stages like selection and sorting for size, maturity and soundness, washing and alkali dipping. The grape bunches were selected from the same lot to ensure uniformity of physical characteristics of the dried grapes. In order to prevent infection of intact grapes by bacteria or fungi, the spoiled berries were discarded from grape bunches. The selected samples were cleaned with tap water to make them free of dust and foreign materials. The vacuum oven method was used to measure moisture content of grapes before and after drying. The sugar content and acidity were used for evaluating maturity of grapes and depending upon the stage of maturity of grapes, the average sugar content was around 23 brix and acidity between 3.5% to 8% with its initial moisture content ranging between 74% to 78% (wet basis).

Chemical pretreatment was also applied to the grapes. This increases water permeability of the grapes through waxy cuticle [8], which is more helpful for increasing the drying rate [9]. For this, grapes were dipped for approximately three minutes in dipping solution consisting of a mixture of 2.5% dipping oil and 2.0% K_2CO_3 as it gives better quality raisins with increased drying rates [10]. After chemical pretreatment, 10 kg of grape bunches were halved and spread out uniformly on five aluminium trays which were then placed in the drying chamber. For quantitative evaluation of natural convection solar dryer, open sun drying and shade drying were also carried out for 10 kg batch size. Grape samples from the same lot were spread on aluminium trays and were dried in open sun and under the shade.

During the experiment, ambient data (i.e., solar irradiance, temperature and relative humidity) as well as inside temperature of the drying chamber and mass of grapes (for all three methods) were recorded between 8.00 a.m. to 5.00 p.m. every hour. Hot air was allowed to flow in the drying chamber during daytime only and the air heater inlet was kept close using damper plates during nighttime. The open sun and shade drying samples were also kept in closed container during nighttime. Drying was continued everyday until the samples achieved the desired final moisture content. The reduction in weight of grapes were determined by weighing all samples from the three drying methods. After completion of the drying experiment, the dried samples were used to ascertain the final moisture content and sensory evaluation of raisins produced.

Sensory evaluation was carried out to estimate organoleptic qualities of raisins produced by each drying method. For determining the quality of raisins, color, taste and texture are the main attributes for estimating the quality and consumer acceptance of raisins produced [11]. The overall quality of each dried sample was assessed by five taste judges and asked to make a categorical rating of the sample. After drying and before carrying out the sensory evaluation, all samples were washed in tap water and dried at room temperature. This is the normal procedure commonly used in commercial raisins manufacturing. Since chemical pretreatment is carried out before drying to increase the drying rate of the grapes, the chemical residues must be removed by washing with tap water. To remove the water particles on the surface of the raisins, a few minutes of drying is carried out. Washing and drying gives an added advantage because the raisins also attain its original color.

For sensory evaluation, the raisins were placed in a coded paper and presented to all the five test judges. In addition to sensory evaluation, test judges were asked to record any additional comments they wished to make about the quality of the product. The judges were asked to evaluate the product on a hedonic scale [12], with the following rating: nine = like extremely; eight = like very much; seven = like moderately; six = like slightly; five = neither like nor dislike; four = dislike slightly; three = dislike moderately; two = dislike very much; and one = dislike extremely.

The performance of drying method is determined in terms of efficiency (η) of the dryer which is defined as the ratio of heat utilized in evaporating the moisture from grapes during drying period to that of total solar insolation on the collector during drying and is given by:

$$\eta = \frac{\lambda \sum M_{ev}}{3600 \sum G_T(t)\, A_c} \times 100 \tag{1}$$

where, M_{ev} = mass of water evaporated in one hour,
λ = latent heat of water evaporation,
G_T = solar irradiance on the collector surface (w/m^2), and
A_c = collector area in m^2.

For comparison purpose, the drying rate constants (which indicated the drying rate of agricultural produce during drying process) for solar dryer, open sun, and shade drying were also determined. In single layer drying of any agricultural produce, numerous models have been proposed to determine the rate of moisture loss with time. The flow of moisture from the product is considered as analogous to the flow of heat from a body immersed in the cold fluid. By treating moisture removal phenomenon from the agricultural produce similar to convective heat loss from the hot bodies, (Newton's law of cooling) drying rate should be proportional to difference in moisture content between the produce to be dried and equilibrium moisture content at drying air state [13]. Mathematically it can be written as:

$$dM/dt = -k\,(M - M_e) \tag{2}$$

where, M = moisture content of produce on dry basis at any time t, (kg/kg)
M_e = equilibrium moisture content of produce, (kg/kg), and
k = drying rate constant (hrs^{-1}).

The solution of Eqn. (2) yields to a single-term exponential equation, which is generally used to fit drying curves of various agricultural produce:

$$\text{Moisture Ratio } (MR) = \frac{M - M_e}{M_o - M_e} = A_o \exp(-k_o t) \tag{3}$$

For composite nature of some agricultural produce, Eqn (3) was found to be inadequate in predicting the moisture loss. For such materials the modified empirical relation (Page's equation) gives better results [14] and Page's equation is given by:

$$MR = \frac{M - M_e}{M_o - M_e} = \exp(-k.t^N) \quad (4)$$

where N is another drying constant of Page's equation.

The value of equilibrium moisture content (M_e) of raisins can be computed by using the well-known GAB equation. The analysis of the obtained data was carried out by using non-linear regression method. It is obvious that the solar drying constants k and N of Page's equation, thus obtained will be different than those drying constants obtained for earlier controlled steady-state conditions of drying air [15, 16] in mechanical drying.

4. RESULTS AND DISCUSSION

A series of experiments were conducted during the typical summer days at the School of Energy and Environmental Studies, Indore, India. The climatic data, i.e., total solar irradiation, daily maximum and minimum temperatures, average ambient temperature and air temperature inside the dryer during the successive days of drying experiments were recorded. The diurnal variation of ambient air temperature, solar irradiance, collector outlet air temperature and dryer outlet air temperature of solar dryer for a typical day is presented in Fig. 2. It is observed from Fig. 2 that maximum air temperature in drying chamber with the application of solar air heater varied from 65.7°C to 68.3°C and average air temperature varied from 46.19°C to 52.26°C during various drying days. The maximum ambient temperature varied from 35.7°C to 40°C and minimum average temperature varied from 25.9°C to 30.2°C with an average ambient temperature from 33.10°C to 34.78°C during the experimental drying days. The maximum temperature rise obtained from solar air heater during peak afternoon hours on all experimental days was around 30°C (varying between 25.9°C to 33.5°C).

To evaluate the quality of the dried product based from consumer acceptance viewpoint, sensory evaluation was carried out for raisins obtained from each method for both sets. The mean average score

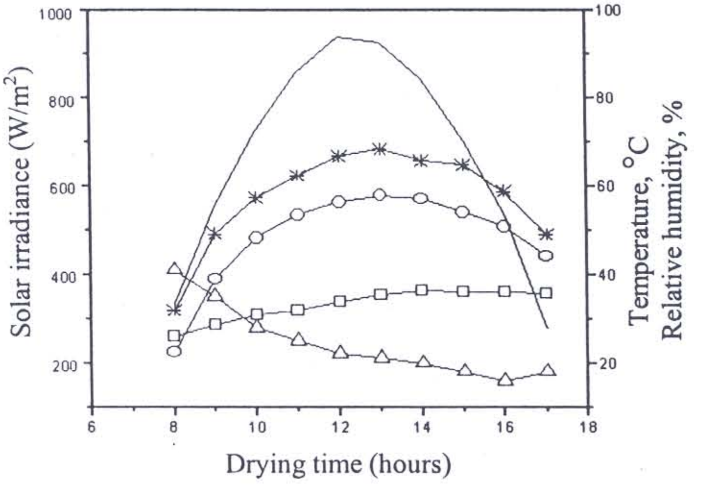

Fig. 2. Diurnal curve for solar dryer for a typical day during drying test for set 1
— solar radiation □ - ambient air temperature
* - dryer inlet air temperature o - dryer outlet temperature
Δ - relative humidity.

value for each method of five test judge's score is given in Table 1. It is observed from this table that organoleptic qualities of solar dryer-dried raisins were found better (with highest score of 40.4) than that of shade drying (score of 37.7) and open sun drying (score of 25.6). More browning was observed in case of open sun drying as compared to indirect drying (solar dryer and shade drying) due to direct exposure of grapes to solar radiation. The laboratory chemical analysis tests [17] were also carried out for raisins obtained from the three drying methods and the results are given in Table 2. From this table, it is observed that the organoleptic qualities of raisins obtained from solar dryer are higher than those obtained from open sun and shade drying. The value of non-enzymatic browning was also higher for open sun drying than that for shade drying and solar-dryer drying. This indicates that results obtained in chemical analysis support the sensory evaluation results.

The performance of solar dryer was evaluated in terms of drying efficiency on hourly basis. The variation of drying efficiency with drying time is shown in Fig. 3 for set 1 and Fig. 4 for set 2. It is observed from these figures that the hourly values of drying efficiency increases slightly with time on each day but decreases from day to day. This increase in hourly values of drying efficiency during morning hours is due to increase in drying air temperature, while during afternoon it can be attributed to the utilization of heat stored in the product and solar air heater. Similarly the decrease in drying efficiency from day to day is due to reduced moisture content in the product and the moisture has to come from the inner surface, which required more time. The overall drying efficiency in case of sub-bunch grape drying (set 1) was 10%, while for full bunch grape drying (set 2) was 7%. It is also observed that the drying efficiency for sub-bunch grape drying was always higher than that obtained for full bunch grape drying.

For determination of drying constants, moisture ratio values of the produce were also calculated and its variation with drying time for solar dryer, open sun and shade drying are shown in Fig. 5 for set 1 and Fig. 6 for set 2. From Fig. 5, it is observed that the moisture content was reduced from 349.59 (%db) to 17 (%db), within 15 days in shade drying and 7 days in open sun drying, while solar dryer dehydrates the grapes within four days. Similarly from Fig. 6, it is observed that the initial moisture content was reduced to final safe moisture content within 17 days in shade drying and 10 days in open

Table 1 Comparative Score for Organoleptic Qualities by Using Sensory Evaluation for Raisins obtained from Solar Dryer and Traditional (Open sun and Shade) Drying Methods

Attributes	Solar-dryer drying	Open sun drying	Shade drying
Color and appearance	8.0	4.6	7.5
Texture	7.8	5.5	7.4
Taste	8.0	5.3	7.6
Flavor	8.1	5.2	7.2
Overall acceptability	8.5	5.0	8.0
Total (50)	40.4	25.6	37.7

Table 2 Comparative Chemical Analysis Results of Raisins obtained from Solar Dryer and Traditional (Open sun and Shade) Drying Methods

Chemical parameter	Solar-dryer drying	Open sun drying	Shade drying
Moisture content (%)	15.44	14.71	15.12
Reducing sugar content (%)	69.74	66.32	68.05
Non-reducing sugar content (%)	10.73	16.53	13.46
Total sugar content (%)	80.47	82.85	81.35
Tartaric acid content (%)	0.30	0.30	0.30
Non-enzymatic browning (O.D. Value)	0.078	0.414	0.25

sun drying while solar dryer dehydrates the grapes within six days. It is also observed from these figures that for successive days during nighttime when no air was blown over the three samples the weight of product continued to decrease. It indicates that the heat stored in solar air heater and product during the day was still effective during the nighttime.

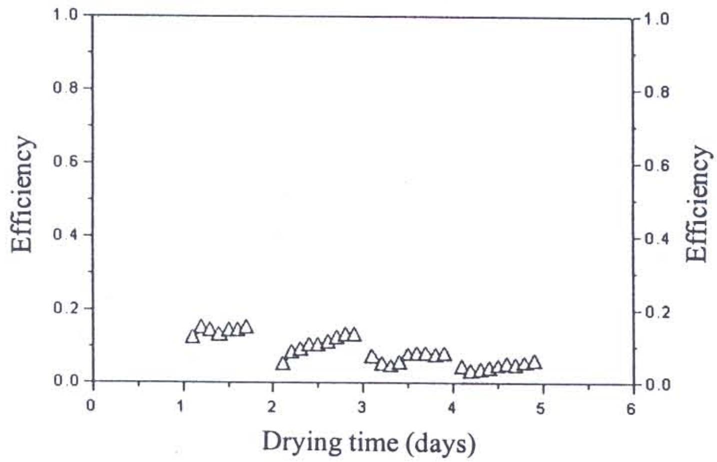

Fig. 3. Variation of hourly drying efficiency (Δ) of the solar dryer for set 1

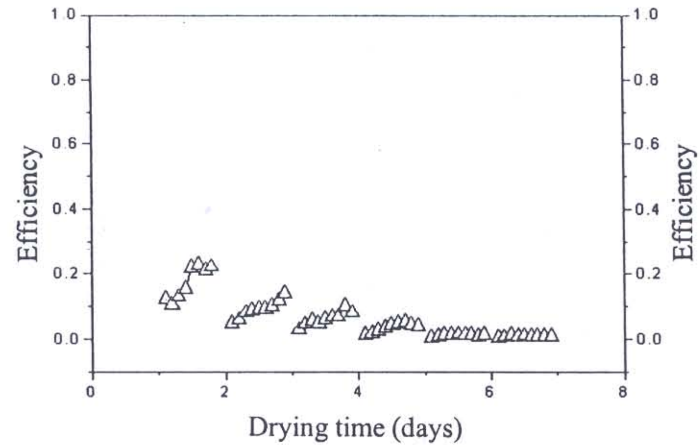

Fig. 4. Variation of hourly drying efficiency (Δ) of the solar dryer for set 2

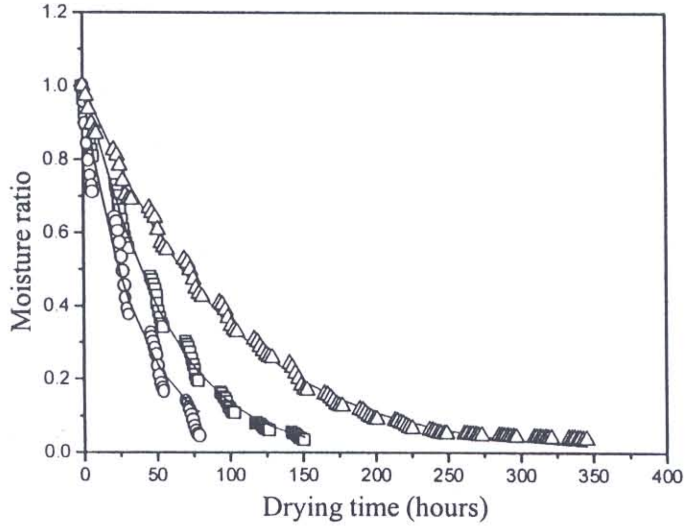

Fig. 5. Variation of moisture ratio with drying time for set 1: Δ - shade drying
□ - open sun drying O - solar dryer drying — Page's predicted

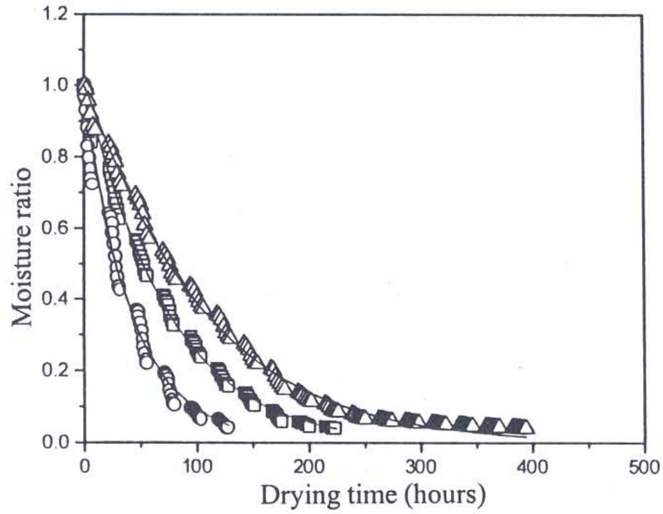

Fig. 6. Variation of moisture ratio with drying time for set 2: Δ - shade drying
□ - open sun drying O - solar dryer drying — Page's predicted

For comparison purpose, the drying constants for solar dryer, open sun and shade drying were also determined. It is obvious that solar drying constants *k* and *N* of the Page's equation, thus obtained will be different than the drying constants obtained earlier for controlled steady-state conditions of heated air in mechanical dryer [15, 16]. The solar drying constant *k* and *N* of the Page's equation for sets 1 and 2 obtained from the three drying methods are given in the Table 3 along with their statistical parameters, coefficient of determination (R^2) and Chi square (χ^2). From this table, it is observed that the value of drying constant *k* is higher in solar-dryer drying (though R^2 value was less) than its value for open sun and shade drying. In case of drying using solar dryer, the value of *k* for sub- bunch grape drying and full bunch grape drying is almost the same while the value of *N* for sub-bunch grape drying is slightly higher than its value for full bunch grape drying. It is also seen that the value of *N* for open sun drying is higher than its value for solar dryer and shade drying. The values of drying constant *k* were determined for the case of thermosyphan solar drying (Table 3) with humidity controlled heated air drying conditions [15] for temperature 50°C, with humidity ratios of 0.010, and ambient heated air conditions drying [16] at temperature 50°C. It is observed that the value of *k* is significantly less (0.028) in natural convection solar dryer than the values for heated air in forced flow mode (0.040 in case of heated ambient air and controlled conditions).

Table 3 Values of Drying Constant *k* and *N* for Sets 1 and 2 obtained from Solar Dryer and Traditional (Open Sun and Shade) Drying Methods using Page's Equation

Constant parameter	Set 1			Set 2		
	Solar-dryer drying	Open sun drying	Shade drying	Solar-dryer drying	Open sun drying	Shade drying
k	0.028	0.012	0.008	0.028	0.010	0.007
N	1.001	1.117	1.069	0.969	1.067	1.065
R^2	0.957	0.989	0.995	0.982	0.996	0.996
χ^2	0.004	9.7×10^{-4}	3.8×10^{-4}	0.002	3.5×10^{-4}	3.3×10^{-4}

5. CONCLUSIONS

The developed solar dryer is capable of producing average temperature of nearly 50°C,which is the optimum for dehydration of grapes to obtain better quality raisins. The score of sensory evaluation for organoleptic qualities of solar dryer and traditional (shade and open sun) drying was in decreasing order, respectively. The overall efficiency of solar dryer was 10% for sub-bunch grapes and 7% for full bunch grapes drying. The value of drying constant, *k* was higher in solar-dryer drying than in open sun and shade drying. The value of drying constant *k* for open sun drying was higher than its value for shade drying. The drying time is also reduced by 73% and 43% as compared to shade drying and open sun drying.

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