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Modeling and Experimental Studies on Solar Crop Dryer Coupled with Reversed Absorber Type Solar Air Heater

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Abstract**—**The experiment was carried out to study the performance of solar crop dryer coupled with reversed absorber type solar air heater (SD2). Excel software is used to analyse the raw data obtained from the drying experiment to develop a model. An attempt is made in this paper to correlate the collector efficiency, dryer efficiency and pick-up efficiency. All these efficiencies are dependent on the parameters such as solar flux, ambient temperature, collector outlet temperature and moisture content. The simulation equation was developed to predict the values of collector efficiency. The parameters a, n and drying constant k were determined from a plot of curve using a drying models. Experimental data of drying red chili in conventional solar dryer and solar dryer coupled with reversed absorber solar air heater was compared by fitting with three drying models. The moisture content will be rapidly reduced in solar dryer with reversed absorber due to higher drying temperatures. The best fit model was selected to describe the drying behavior of red chili. For SD2 the values of the coefficient of determination (R^2=0.997), mean bias error (MBE=0.00026) and root mean square error (RMSE=0.016) were used to determine the goodness or the quality of the fit. Pages model showed a better fit to drying red chili among Newton model and Henderson & Pabis model.

Keywords**—**Solar dryer, red chili, reversed absorber, reflector, Buckingham pi theorem, drying model.

I. Introduction

FARMERS use a traditional open sun drying technique to dry an agriculture food product. The main disadvantage of this process is spoilage of food product due to rain, wind, moist, dust, birds and animals, deterioration of the material due to insect infestation and fungal growth. This traditional method is comparatively a slow process than a solar dryer with solar air heater particularly in locations with good sunshine during the harvest season. It is possible to maintain a required drying temperature in solar drying to improve the quality of product and reduce the losses. Also the traditional process is highly time consuming, labor intensive, and requires large area. In such conditions, a solar-energy crop dryer is an emerging technology. During an open sun drying, the crop losses and deterioration are immensely affected due to change in climatic conditions. It increases the interest in utilization of solar dryers. The drying is a process of reducing the moisture content of the product to a level of equilibrium moisture content that prevents deterioration. The period for which deterioration stop normally termed as the "safe storage period" [1]. Drying processes continues until the vapour pressure of the moisture in the product equals to the vapour pressure of the moisture held in the environment [1], [2]. Properly designed solar air heater may give sufficient rise in temperature of air which is suitable for drying of some of the agricultural food products [3]-[7]. In India an average daily solar radiation is received in the range of 5-7 KW/m² and more than 275 days are with good sunshine in a year [8].

The main purpose of this research is to evaluate an experimental performance of a solar crop dryer using a solar air heater with two absorber plate and reflector.

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II. Materials and Methods

A. Red Chili

Chili is a potential cash crop in India and has a good export market. The red chili used in this study is obtained from Farm, Nerpinglai, Amravati (District), Maharashtra, India.

B. Experimental Set Up

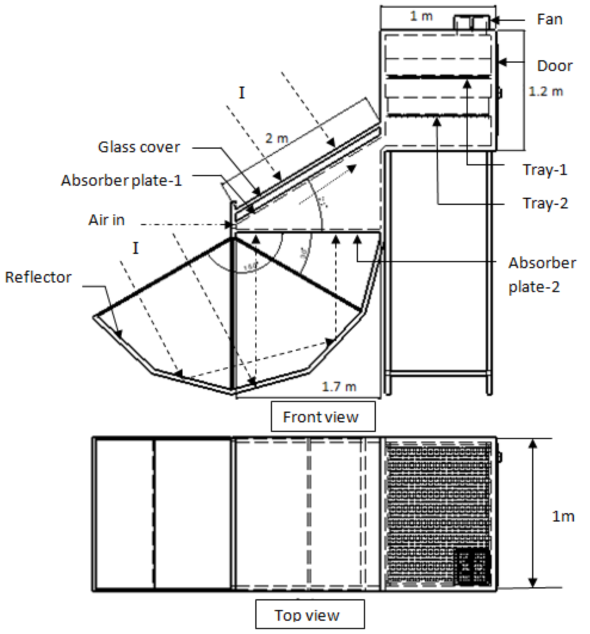

Fig. 1 Schematic diagram of solar crop dryer with reversed absorber plate and reflector (SD2)

A schematic diagram of a proposed force circulation single glazing solar crop dryer with a reversed absorber plate is shown in Fig. 1. It consists of a 4 mm thick glass cover, two black painted aluminium absorber plates and a reflector. A reflector in a shape of polygonal form (pieces of five equal flat surfaces) is positioned under the reversed absorber-II. The collector dimensions are 1 m wide and 2 m long. The gap between a glass cover-I and absorber plate-I surface was maintained at 25 mm. The solar air heater is oriented to face south and tilted at 31 °C angle from the horizontal plane to maximize the solar radiation incident on the solar collector. A fraction of polygonal shape reflector (segment of five equal flat pieces) is placed under the flat plate absorber-II to introduce solar radiation from below. The air flows between two absorber plate-I & II where it gains the thermal energy from absorber plate-I & II. Thus the outlet air temperature of the air heater is maximized. The outlet air from solar air heater is used for chili drying. The experimental setup mainly consists of a solar air heater with reversed absorber, reflector, drying chamber. Exhaust fan is provided to maintain the mass flow rate of air. Six pre calibrated RTD (pt100) temperature sensor with ±0.5 °C accuracy were fixed at different locations of the solar dryer which are connected to a digital temperature indicator (having 0.1 °C resolution). Pyranometer of range 1999 W/m² and accuracy ±10, anemometer range 20 m/s and accuracy ±0.01 m/s, electronics weighing scale range: max 20 kg, min 20 g and accuracy: ±0.01 g, (make- ASTRO digital scale), wet and dry bulb hygrometer (Make- OMSONS) are used.

The drying cabinet was constructed with insulated wooden walls of dimensions 1 m x 1 m cross sectional area and 1 m height. Exhaust fan (Capacity 300 m³/h) is provided at the top of dryer cabin. A fan is used to maintain a constant flow in the collector and drying cabinet to maintain a negative pressure during collection of heat, reduce heat losses and increase evaporation rate of moisture from the agricultural food product. Drying cabinet is capable of holding 10 Kg (each tray 5 Kg) chili per batch. For circulation of air, a 90% perforation and a gap of 50 mm is maintained between the trays.

C. Period of Experimentation

Experimental study was conducted from October 22 to November 11, 2015 in the calm wind. During this period, the chili was collected from farm every 10-15 days. Experimental site: Latitude 21.1458 North, Longitude 79.088 East and altitude 12 m from ground.

D. Sample Preparation

Fresh red chili was obtained from farm, Nerpingalai, India. The experiments were conducted (8 am to 6 pm) for 10 sunshine hours. For each experimental set 10 Kg of fresh red chili was used. Fresh red chili samples were stored before each experimental set at 5 °C and used within 1 day of purchase. Before drying, the chili was washed by potable water and placed on plastic trays to drain out excess water. Drying was carried out without any pretreatment.

III. Mathematical Model

While working on the solar air heater with reversed absorber it is necessary to decide the parameters that affect the efficiency of the solar air heater. This is possible by formulating the mathematical model through which a quantitative relationship would be established between a various dependent and independent parameters of solar air heater with reversed absorber. During experimentation, data were collected and mathematical model was developed. Air temperature and solar flux are considered while developing model.

A. Design of Experimentation

In the experiments, dimensional equation is solved for a phenomenon that reduces the number of independent variables. This is attained by applying Buckingham's π theorem. In a system involving 19 independent variables and four primary dimensions formed a 15 numbers of π terms (19-4=15). The following variables are influencing on an efficiency for a presented shape of solar air heater.

$$\eta c = f\,(I, Ap_1, T_i, T_f, Cp_a, \alpha g, \alpha p, \tau g, h, U, v, \rho_{air}, \rho, A_r, Ap_2, \varepsilon, kp, \beta)$$

Dependent Variable

Ƞc - efficiency of solar air heater, %, [M° L° T° θ°]

Independent Variable

Ap_1 - area of collector plate-I, m², [L²]
Ap_2 - area of collector plate –II, m², [L²]
A_r - area of reflector, m², [L²]
Cp_a - specific heat at constant pressure, J/kg K, [$L^2T^{-2}\theta^{-1}$]
H - convective heat transfer coefficient, W/m²K [$MT^{-3}\theta^{-1}$]
U - overall heat loss coefficient from sides of dryer, W/m²K, [$MT^{-3}\theta^{-1}$]
I - solar radiation on inclined absorber plate, W/m², [MT^{-3}]
Kp - thermal conductivity of collector plate, W/mK, [$MLT^{-3}\theta^{-1}$]
T_i - collector inlet temperature, K, [M° L° T° θ¹]
T_f - collector outlet temperature, K, [M° L° T° θ¹]
V - velocity of air, m/s, [LT^{-1}]
A - absorptivity, [M° L° T°]
B - tilt angle of absorber plate, degree, [M° L° T°]
E - emissivity, [M° L° T°]
P_{air} - air density, kg/m³, [ML^{-3}]
τ - transmitivity, [M° L° T°]

Above equation can be written as,

$$f1\,(\eta c, I, Ap_1, T_i, T_f, C_{pa}, \alpha g, \alpha p, \tau g, h, U, v, \rho_{air}, \rho, A_r, Ap_2, \varepsilon, kp, \beta) = 0$$

Above equation can be written as,

$$f\,(\eta c, I, Ap_1, Ti, Tf, C, \alpha g, \alpha p, \tau g, h, U, v, \rho air, \rho, Ar, Ap_2, \varepsilon, kp, \beta) = 0$$

B. Formulation of Data Based Model

The present experiment is characterized by 18 independent π terms and one dependent π term. During experimentation, the first independent π term shows the geometrical property, while second π term shows the flow property, third π term shows the fluid property and fourth π term relates with temperature property. By applying Buckingham's π theorem,

- Total number of variables = 19
- Number of π terms = n-m = 19-4 = 15
- Geometric property – A
- Flow property – v
- Fluid property – ρ
- Temperature property – k

Since,

$$f1\,(\pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6, \pi_7, \pi_8, \pi_9, \pi_{10}, \pi_{11}, \pi_{12}, \pi_{13}, \pi_{14}, \pi_{15}) = 0$$

From above equation, by substituting the value of π_1 to π_{15}

$$f\{\frac{I}{v^3\rho}, \frac{kT_i}{Ap_1^{1/2}\,v^3\rho}, \frac{kT_f}{Ap_1^{1/2}\,v^3\rho}, \frac{v\rho CAp_1^{1/2}}{k}, \alpha_p, \alpha_g, \tau_g, \frac{Ap_1^{1/2}h}{k}, \frac{Ap_1^{1/2}U}{k}, \frac{Ar}{Ap_1}, \frac{Ap_2}{Ap_1}, \varepsilon, \rho', \eta_c, \beta\} = 0$$

$$\eta_c = f\,[\frac{I}{v^3\rho}, \frac{kTi}{Ap_1^{1/2}\,v^3\rho}, \frac{kT_f}{Ap_1^{1/2}\,v^3\rho}, \frac{v\rho C_{pa}Ap_1^{1/2}}{k}, \alpha_p, \alpha_g, \tau_g, \frac{Ap_1^{1/2}h}{k}, \frac{Ap_1^{1/2}U}{k}, \frac{A_r}{A_{pa}}, \frac{Ap_2}{Ap_1}, \varepsilon, \rho', \beta]$$

$\frac{A_r}{Ap_1}, \frac{Ap_2}{Ap_1}$ are non influencing parameters. Now $[\frac{v\rho C_{pa}Ap_1^{1/2}}{k}$, αp, αg, τg, $\frac{Ap_1^{1/2}h}{k}, \frac{Ap_1^{1/2}U}{k}$, ε, ρ΄, β] are constant. Therefore,

$$\eta_c = f\,[\frac{I}{v^3\rho}, \frac{kT_i}{Ap_1^{1/2}\,v^3\rho}, \frac{kT_f}{Ap_1^{1/2}\,v^3\rho}]$$

$$y = \phi\,[(X_1)^{a1}, (X_2)^{a2}, (X_3)^{a3}] \quad (1)$$

by solving (1) using multiple linear regression method (using Microsoft excel), we get,

$$\phi = 0.31,\ a_1 = -0.00171,\ a_2 = -0.000231,\ a_3 = 0.0010982$$

From (1),

$$\eta_c = 0.31\left[\frac{I}{v^3\rho}^{-0.00171} \frac{kT_i}{Ap_1^{1/2}\,v^3\rho}^{-0.000231}, \frac{kT_f}{Ap_1^{1/2}\,v^3\rho}^{0.0010982}\right] \quad (2)$$

Thus, a mathematical model is developed, and validated by the data generated by the experimental observations.

IV. Mathematical Modelling of Drying Curves

Table I shows the thin layer drying equation which was tested to select the best model for describing the drying curve equation in mathematical modeling of drying process by solar dryer [9]-[17].

Equations (3)-(11) were used to calculate a system performance and the drying characteristics. The moisture content on dry basis was calculated using [18]:

$$\text{Initial moisture content } M_i = \frac{W_O - W_d}{W_d} \quad (3)$$

$$\text{Final moisture content } M_f = \frac{W_{wet} - W_d}{W_d} \quad (4)$$

W_o = Sample (Chili) weight at t=0 (kg), W_d = mass of dry matter in sample (kg), W_{wet} = mass of wet matter in sample after drying in a solar dryer, W_t= weight of sample (Chil) at any time't' (kg).

Equation (5) was used to calculate the instantaneous moisture content (Mt) at any given time on dry basis [19]

$$M_t = \left[\frac{(M_O+1)*W_o}{W_t} - 1\right] = \frac{(W_t - W_d)}{W_d} \quad (5)$$

By fitting moisture content and time to a thin layer drying equation, a drying rate constant 'k' was derived. The change in weight of chili over time is used to calculate the moisture change over time [20].

$$\text{Moisture ratio MR} = \frac{M_t - M_e}{M_o - M_e} = e^{-kt} \quad (6)$$

where M_e = Equilibrium moisture content, M_o = Initial moisture content.

Drying rate, dryer thermal efficiency and pick-up efficiency are the main characteristics used for performance estimation of any solar drying system [21]. Drying rate is proportional to the difference of final moisture content and the equilibrium moisture content in the food product [22]. It can be expressed as thin layer equation. Mathematically,

$$\text{Drying rate } dM/dt = -k\,(M_t - M_e) \quad (7)$$

Dryer thermal efficiency was computed from [19]:

$$\eta_d = \frac{m_w h_{fg}}{\dot{m}_a C_{pa}\,(T_d - T_i)} \quad (8)$$

where $\dot{m}_a$- air mass flow rate in the dryer, C_{pa} - specific heat of air, T_d - dryer air temperature, T_i - air temperature at collector inlet which can be taken equal to ambient temperature, h_{fg} - latent heat of evaporation of water, m_w - mass of water evaporated.

The dryer pick-up efficiency was computed from [19]:

$$\eta_p = \frac{m_w}{\dot{m}_a \Delta t (X_2 - X_1)} \quad (9)$$

where m_w - mass of moisture evaporated in time Δt, $\dot{m}_a$ - mass flow rate of air, W_{ce} - absolute humidity of air at dryer exit, W_{ci} - absolute humidity of air at dryer inlet.

TABLE I
Drying Models

NSN	Model name	Model
11	Newton	$MR = e^{-kt}$
22	Page	$MR = e^{-kt^n}$
33	Henderson & Pabis	$MR = a * e^{-kt^n}$

Drying kinetics of chili was determined by using three drying models. Table I shows the drying models.

Initial moisture content of chili can be obtained by drying in air oven at a temperature of 120 °C, in order to obtain constant weight. It had an initial moisture content of 80%. The quality of the drying model is decided from the highest values of R^2 and the lowest values of MBE and RMSE. These values were calculated to estimate the best drying curve [23].

$$\mathrm{MBE} = \frac{1}{N}\sum_{i=1}^{N}(\mathrm{MR}_{pre,i} - \mathrm{MR}_{exp,i})^2 \quad (10)$$

$$\mathrm{RMSE} = [\frac{1}{N}\sum_{i=1}^{N}(\mathrm{MR}_{pre,i} - \mathrm{MR}_{exp,i})^2]^{\frac{1}{2}} \quad (11)$$

V. Result and Discussion

The performance of the proposed solar crop dryer coupled with reversed absorber type solar air heater was studied and compared with the performance of a conventional solar air heater.

From Figs. 2, 3 and 5, respectively, it can be observed that the average collector efficiency, dryer thermal efficiency and pick up efficiency are significantly increased for the solar air heater with two absorber and reflector than solar air heater without reflector at I avg. =648 W/ m², Ta.avg. =30 °C and wind speed =1 m/s. It seems that the solar air heater with reflector is more efficient than without reflector. This observation is consistent with findings from other studies which show that the heat gain by absorber plate–II is appreciable [24]-[26].

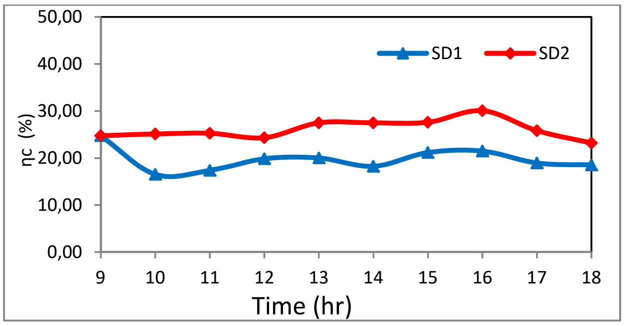

Fig. 2 Comparative analysis of collector efficiency between SD2&SD1

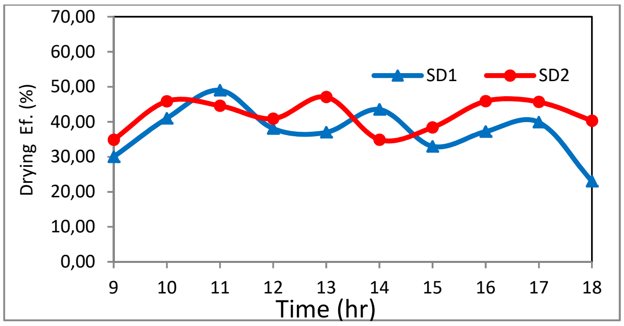

Fig. 3 Comparative analysis of dryer efficiency between SD2&SD1

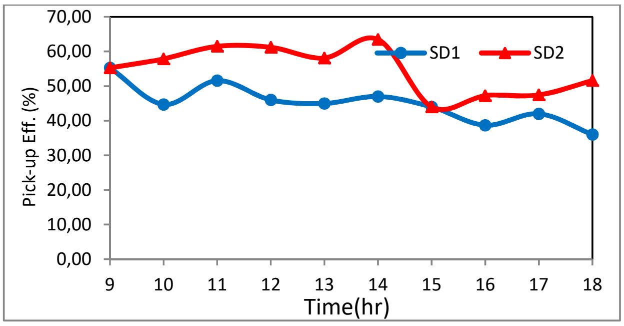

Fig. 4 Comparative analysis of pick-up efficiency between SD2& SD1

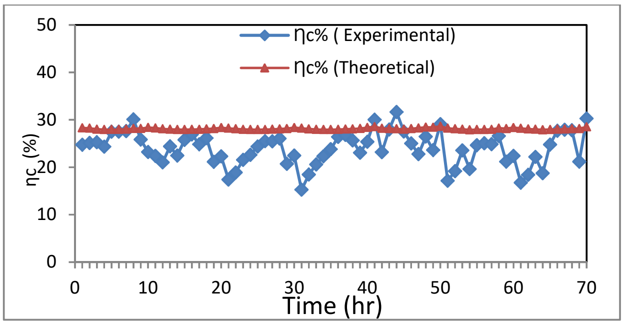

Fig. 5 Comparative analysis between experimental and theoretical collector efficiency for SD2

Mathematical model was developed to find a thermal efficiency which is depending on the independent parameters such as solar flux, ambient temperature and collector outlet temperature. Solar dryer without reflector attained efficiency is lesser than the theoretical efficiency attained from the mathematical model. Efficiency achieved from the formulation is 28% and efficiency attained from the experiment values of π terms is 24% for solar dryer with two absorber plate and reflector.

From Fig. 5, it can be observed that most of experimentally attained efficiency is lesser than the theoretical efficiency.

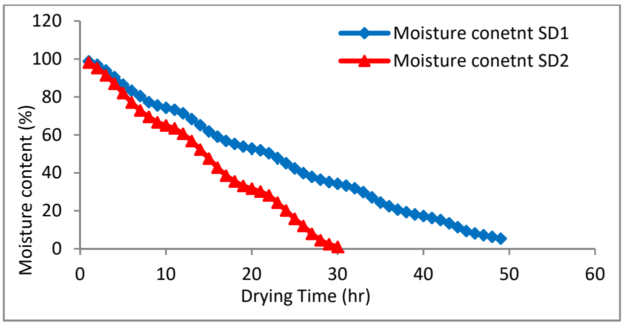

Fig. 6 Hourly variation of moisture content, db (%) with drying time

Fig. 6 shows the hourly variation of the moisture content with drying time. It can be observed that the moisture content in a chili above the equilibrium moisture content is for shorter time in solar dryer (SD2) than SD1. Fig. 7 shows the profile of the drying rate versus drying time. Drying rate was found higher in the solar dryer with reflector than solar dryer without reflector and open sun drying because of high drying temperature which reduced the effect of variation in relative humidity during sunshine hours. This means that the time required to dry the chili to reach equilibrium moisture content is shorter. The higher the drying temperature and lower relative humidity boost the rate of evaporation of water from the material. Due to rise in temperature of crop, the vapour pressure developed inside the chili would be higher than the vapour pressure in atmosphere. Pressure difference produced a driving force due to which evaporation rate of moisture present in food product increased [27].

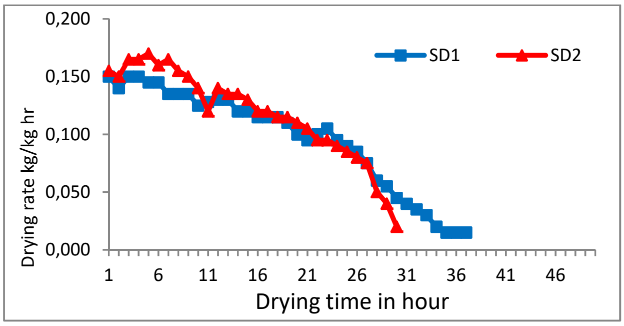

Fig. 7 Hourly variations in drying rate with drying time

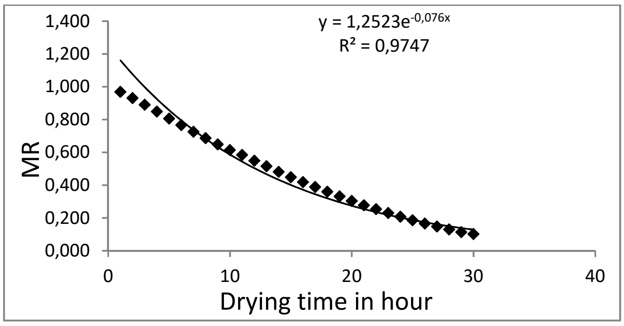

Fig. 8 Plot of Moisture ratio versus drying time (Newton's model) for Solar dryer with reversed absorber (SD2)

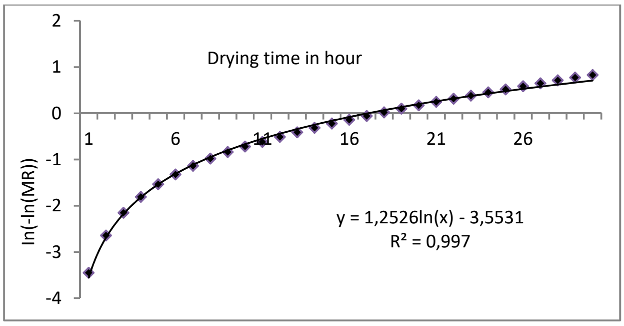

Fig. 9 ln (-ln MR) versus drying time (Page's model) for Solar dryer with reversed absorber (SD2)

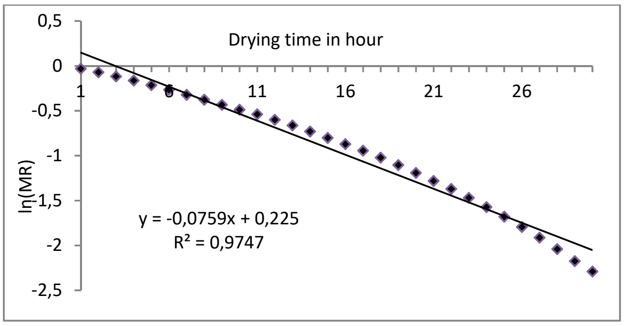

Fig. 10 ln(MR) versus drying time (Henderson's and pabis model) for Solar dryer with reversed absorber (SD2)

Experimental data were used to represent a graph between changes in moisture content and drying time. Constants are calculated by graphical method. Tables II-IV show a value of model constant, MBE, RMSE and R^2. A drying model with highest value of R^2 and lowest MBE and RMSE is selected to estimate the drying curve is the best [22].

$$\ln(-lnMR) = \ln(k) + nln(t) \quad (12)$$

Equation (12) shows the relationship between ln(-ln MR) and t. It is the logarithmic equation which gives curve as shown in Fig. 9 and obtained the value k = 0.029 and the value of a = 1.252. Henderson and Pabis equation can also be written by:

$$\ln MR = -kt + \ln a \quad (13)$$

From (13), a plot of ln MR versus drying time gives a straight line with intercept = ln a, and slope = k as shown in Fig. 10.

TABLE II
CONSTANT VALUE FITTING OF NEWTON MODEL

SN	Dryer type	Drying model	Model constant	MBE	RMSE	R^2
1	SD1	Newton	k = 0.06	0.00132	0.036	0.99
2	SD2	Newton	k = 0.07	0.00389	0.062	0.97

TABLE III
CONSTANT VALUE FITTING OF PAGE MODEL

SN	Dryer type	Drying model	Model constants	MBE	RMSE	R^2
1	SD1	PAGE	k=0.0271 n=1.212	0.00020	0.014	0.998
2	SD2	PAGE	K=0.029 n =1.252	0.00026	0.016	0.997

TABLE IV
CONSTANT VALUE FIITING OF HENDERSON AND PABIS

SN	Dryer type	Drying model	Model constants	MBE	RMSE	R^2
1	SD1	HENDERSON & PABIS	a=0.854 k=0.061	0.017	0.132	0.990
2	SD2	HENDERSON & PABIS	a=1.492 k=0.075	0.00332	0.058	0.974

Results are given in Tables II-IV. The Pages drying model has the lowest values of MBE and RMSE and the highest value of R^2 compared to Henersons and Pabis and Newton model, so Pages model is the suitable model for Chili drying.

VI. Conclusion

i) This study shows that for a solar dryer using double absorber with reflector and single absorber solar air heater, there is a significant increase in the collector efficiency, dryer efficiency and pick-up efficiency of the solar dryer using double absorber with reflector solar air heater. Further, results showed that at constant mass flow rate, the difference in air temperature is directly proportional to solar radiation (I). The maximum thermal efficiency obtained is 30% and 21% for solar air heaters with reversed absorber and single absorber respectively for air mass flow rate of 0.0269 kg/s.

ii) A simplified simulation equation (2) is developed, This equation can be used to evaluate the values of collector efficiency for known data of solar flux (I), ambient temperature of air (Ta) and outlet temperature of solar heater. It has also been estimated that the simulation equation (2) predicts the values of efficiency with an average standard error of estimation of 5.39 and with R2 values of 0.979, when compared with experimentally determined values. Thus (2) is justifiable by taking into consideration all of the experimental errors themselves. Therefore above equations may be used with confidence for predicting the collector efficiency and can be considered as design equations for two absorber plate solar air heater with reflector.

iii) This paper also presents the mathematical modeling of dried Chili in solar drying. Three drying models have been used in order to illustrate the best drying model for Chili by solar dying at constant mass flow rate. To find the best drying model is through the values of R^2, MBE and RMSE. Based on the drying model curves, among the Newton's, Henderson & Pabis and Page's drying model, the page's model is showed a better fit to experimental data and describing the drying curves of red chilli. The Page's model was resulted in the highest value of R^2 and lowest values of MBE and RMSE.

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