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Drying Nerium Oleander in an Indirect Solar Dryer Using Phase Change Material as an Energy Storage Medium

S. M. Shalaby and M. A. Bek

***Abstract*—In this work, the Nerium Oleander was dried at its prescribed drying temperature (50±2.5 ℃) in indirect solar dryer (ISD) using phase change material (PCM) as energy storage medium. 12 kg of paraffin wax were used as a latent heat thermal storage. From the experimental obtained results it is found that the ISD implementing PCM as thermal storage medium successfully maintains the temperature of drying air around 50 ℃ for seven consecutive hours. It is also found that the temperature of drying air is higher than ambient temperature by 2.5-5 ℃ after sunset for 5 hrs at least. This profile of the temperature of drying air helps reaching the final moisture content of Nerium Oleander after 14 hrs. Nine thin layer drying mathematical models were tested to specify the suitable model for describing the drying behavior of the Nerium Oleander. It was found that Midilli and Kucuk model is convenient to describe the thin layer solar drying of Nerium Oleander.**

***Index Terms*—Solar drying, nerium oleander, energy storage, PCM.**

I. Introduction

Medical plant loses its valuable contents when it is exposed to direct solar radiation or when treated with high oven temperature. So there is deep need for a new design for the indirect solar dryer that is able to dry the medical plants and maintain all its valuable contents at the same time. Moreover, the valuable medical plants will be dried then it will be economically beneficial as a result of storing it and/or exporting it.

Nerium Oleander is used as a decorative tree for both streets and school gardens neglecting its medical content. The chemical analysis of Nerium Oleander indicates a large amount of glycoside as reported in [1], [2]. The glycoside medical component is economically important as it is used in heart treatment [3], [4].

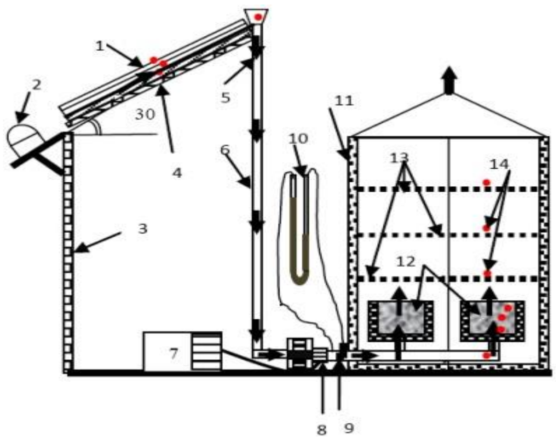
A few types of medical plants are dried using the indirect solar dryer such as mints [5], [6] and thymus [5]. Although most of these studies concern the drying curves and their suitable mathematical modeling description, they ignore the important factor of the best desired plants drying temperature.

The phase change material (PCM) ability to store large amount of thermal energy during its melting process and benefit of it under constant temperature later, makes it excellent tool to improve the solar drying system. Limited researchers [7]-[11] utilized the PCM in solar drying system. Although these studies show that the implementing of the PCM in the solar dryer improves thermal performance of the drying system, it ignores the heat losses. Besides, they do not examine their drying system for drying medical plants.

In this work, for the first time, the Nerium Oleander was dried at its prescribed drying temperature (50±2.5 ℃) in an indirect solar dryer (ISD), in which the PCM storage unit is located at the inner bottom of the drying compartment to reduce the heat losses.

II. Measurements and Experimental Preparation

The ISD was designed and fabricated in the Solar Energy Laboratory workshop, Faculty of Engineering, Tanta University. Complete design details of the air heater, drying compartment and PCM storage unit can be found elsewhere [12]. The ISD implementing PCM was tested using the test rig shown in Fig. 1. The experiments were conducted outdoors during October 2013. The global solar radiation on a (30^o) tilted surface, *I*, was measured using a high precision Pyranometer model MS-802 (sensitivity of 7.03 (μvolts/W m^2)). Calibrated K-Type thermocouples (0 to 1100 ℃) coupled with KYORITSU KEW1011 multimeter were used to measure the temperatures at different locations of the heater and drying compartment as seen in Fig. 1. The temperatures of the drying air at each tray were measured and its average value, $T_{da(av)}$, was obtained. A three-phase induction motor (Type K 120 T, 0.75 HP, 2.5 A, 390 V, 50 Hz, 2610 r/min) coupled with a fan (0.3 m diameter) was used to blow the air to the drying compartment. The air flow rate was controlled and measured with the help of SJ 300 Hitachi inverter and pitot tube, respectively.



1-Solar air heater; 2-Pyranometer; 3-The room wall; 4-The room roof; 5-Flowing air; 6-PVC tube; 7-Inverter; 8-Three phase induction motor coupled with fan; 9-Pitot tube; 10-U tube manometer; 11-Drying compartment; 12-PCM; 13-Trays; 14-Thermocouple positions.

Fig. 1. A schematic diagram of the experimental setup.

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The Nerium Oleander was collected from the faculty of pharmacy's research farm in order to be dried by the ISD. There are several considerations which took place during the drying process. Initially the spoiled plants were discarded to avoid products contamination from bacteria. Moreover, selected plants of same size were chosen carefully to ensure the physical characteristics uniformity. Then the selected plants were cleaned using tab water to remove any undesired materials. Cotton clothes were used to remove any water remains from the surface of the plants.

In order to determine the initial moisture content, the plants were weighed while they were fresh then dried at electric oven for 48 hours on 70 ℃ and the dried products were weighed for the second time. A digital balance, type 300-9213/b 125A, of readability 0.0001 gm was used to measure the mass of the sample every 60 minutes until it reaches a constant weight.

A. Drying Parameters

In this section, the governing equations of the drying process and its basic definitions are introduced. The initial moisture content on dry base M_{0d} is defined as the mass of moisture present in the sample per unit mass of dry matter in the sample [13]:

$$M_{0d} = {(m_0 - m_d)}/{m_d} \tag{1}$$

Similarly, M_{ow} is calculated as follow:

$$M_{0w} = {(m_0 - m_d)}/{m_0} \tag{2}$$

The moisture content M_{td} at any given time on dry base is computed using the following expression as presented in [14]:

$$M_{td} = \left[\frac{(M_{od}+1)m_t}{m_0} - 1\right] \tag{3}$$

M_{tw} can be calculated from the following equation [15]:

$$M_{tw} = 1 - \left(\frac{1}{M_{td}+1}\right) \tag{4}$$

The moisture ratio *MR* is defined as:

$$MR = \frac{(M_t - M_e)}{(M_0 - M_e)} \tag{5}$$

The moisture ratio *MR* is simplified by some investigators [6], [16] to M_t/M_0 because the equilibrium moisture M_e content is significantly less than the initial moisture content M_0. In this case, (5) becomes

$$MR = \frac{M_t}{M_0} \tag{6}$$

The mass shrinkage ratio $(SR)$is defined as [17]:

$$SR = {m_t}/{m_0} \tag{7}$$

The drying thermal efficiency is given as [18]:

$$\eta_d = \frac{mL}{I_{av}At} \tag{8}$$

TABLE I: MATHEMATICAL MODELS APPLIED TO THE SOLAR DRYING CURVES

Model name	Model equation	Reference
Lewis	$MR = \exp(-kt)$	[19]
Page	$MR = \exp(-kt^n)$	[20]
Modified Page	$MR = \exp(-(kt)^n)$	[21]
Henderson and Pabis	$MR = a\exp(-kt)$	[22]
Logarithmic	$MR = a\exp(-kt) + c$	[23]
Two term	$MR = a\exp(-k_0 t) + b\exp(-k_1 t)$	[24]
Modified Henderson and Pabis	$MR = a\exp(-kt) + b\exp(-gt) + c\exp(-ht)$	[25]
Verma *et al*.	$MR = a\exp(-kt) + (1-a)\exp(-gt)$	[26]
Midilli and Kucuk	$MR = a\exp(-kt^n) + bt$	[27]

Moreover, the thin layer drying equations given in Table I [19]-[27] are tested to select the most suitable model for describing the drying curve of Nerium Oleander. For model evaluation, a nonlinear regression analysis is used. The correlation coefficient *R*, the statistical parameter reduced chi-square x^2, and root mean square errors RMSE are used to determine the quality of the fit. The higher value of *R* and the lower values of $x^2$and RMSE are chosen as the criteria for goodness of fit. The reduced chi-square $x^2$and the root mean square errors RMSE are calculated as follows [28]:

$$x^2 = \frac{\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{pre,i}\right)^2}{N-n} \tag{9}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{pre,i}\right)^2}{N}} \tag{10}$$

where $MR_{\exp.i}$ stands for the experimental moisture ratio found in the measurements; $MR_{pre.i}$ is the predicted moisture ratio for this measurement; *N* is the number of observations; and *n* is the number of a model's constants.

III. RESULTS AND DISCUSSIONS

The ISD implementing PCM is used to dry Nerium Oleander on a typical day of October 2013 where the maximum measured values of solar radiation and ambient temperature are 1109 W/m^2 and 31 ℃, respectively as seen in Fig. 2. The variation of the average value of drying air temperature $T_{da(av)}$ is also shown in Fig. 2. The ISD implementing PCM as thermal storage medium successfully maintains $T_{da(av)}$ around 50 ℃ for seven consecutive hours as clearly seen in Fig. 2. It is also seen in Fig. 2 that $T_{da(av)}$ is higher than ambient temperature by 2.5-5 ℃ after sunset for 5 hrs at least. This profile of drying temperature helps reaching the final moisture content of Nerium Oleander after 14 hrs as clearly seen in Fig. 3. The shrinkage ratio is 0.367 as calculated from (6). Variation of moisture ratio of one kg of Nerium Oleander with drying time is shown in Fig. 4. The thin layer drying models given in Table I are applied on the drying curve of Nerium Oleander represented in Fig. 4 and the obtained statistical results are summarized in Table II. From the results of Table II it is seen that Midilli and Kucuk model gives the highest correlation coefficient ($R = 0.9981$) and the lowest reduced chi-square ($x^2 = 0.000336$) and lowest root mean square error ($RMSE = 0.01625$); therefore, it is selected to describe the thin layer drying behavior of Nerium Oleander. The thin layer drying model of Nerium Oleander is obtained as:

$$MR = 1.0073\exp(-0.1365t^{1.1306}) + 0.01t \qquad (11)$$

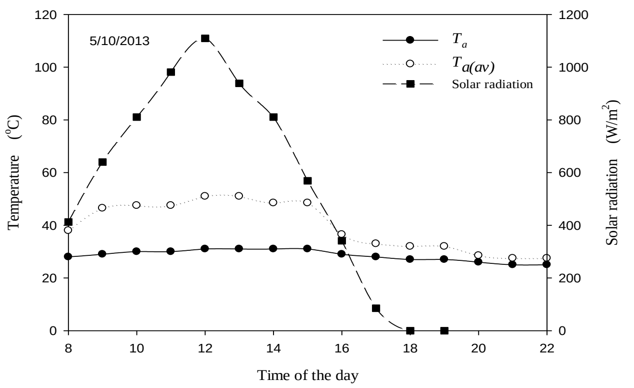

Fig. 2. The variation of drying temperature VS time.

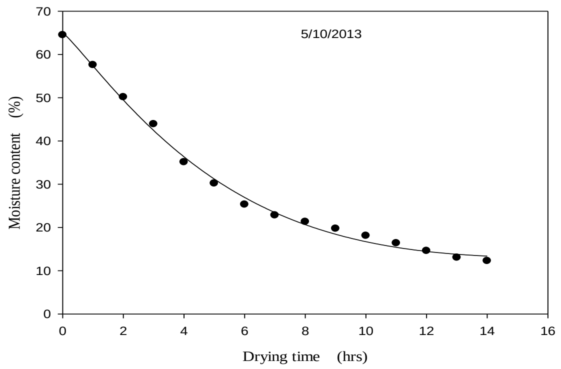

Fig. 3. The variation of moisture content of one kg of Nerium Oleander with the drying time.

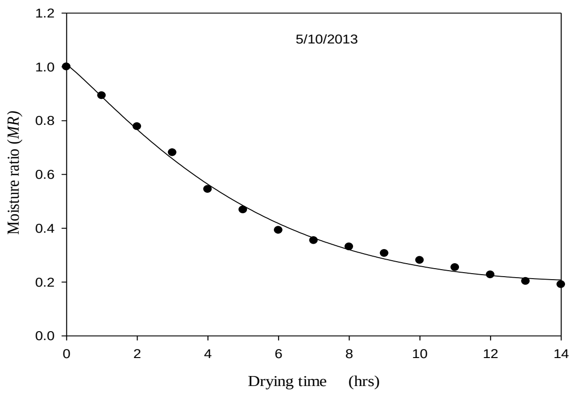

Fig. 4. The variation of moisture ratio of one kg of Nerium Oleander with the drying time.

TABLE II: STATISTICAL RESULTS OF MATHEMATICAL MODELING OF DRYING CURVES FOR NERIUM OLEANDER

Model	Coefficients	R	x^2	$RMSE$
Lewis	$k = 0.1352$	0.9935	0.000962	0.02988
Page	$k = 0.1558$, $n = 0.9282$	0.9946	0.000858	0.02712
Modified Page	$k = 0.1349$, $n = 0.9282$	0.9946	0.000858	0.02712
Henderson and Pabis	$a = 0.9945$, $k = 0.1343$	0.9935	0.001033	0.02976
Logarithmic	$a = 0.9072$, $k = 0.1822$, $c = 0.1206$	0.9972	0.000482	0.01945
Two term	$a = 0.9072$, $k_0 = 0.1822$, $b = 0.1206$, $k_1 = 8.8\times10^{-11}$	0.9972	0.00053	0.01945
Modified Henderson and Pabis	$a = 0.4593$, $k = 0.1822$, $b = 0.4479$, $g = 0.1822$, $c = 0.1206$, $h = 2.2\times10^{-11}$	0.9972	0.000663	0.01945
Verma et al.	$a = 0.8965$, $k = 0.1692$, $g = 3.3\times10^{-11}$	0.9966	0.000591	0.02155
Midilli and Kucuk	$a = 1.0073$, $k = 0.1365$, $n = 1.1306$, $b = 0.01$.	**0.9981**	**0.000336**	**0.01625**

Comparison between experimental moisture ratio and that predicted using Midilli and Kucuk model for Nerium Oleander is shown in Fig. 5. From this figure it is clear that, the established model (11) provided good conformity between experimental and predicted moisture ratios, and the predicted data generally banded around a 45 ^{o} straight line. This means that, this model is valid in describing the thin layer solar drying behavior of Nerium Oleander for given operating drying parameters.

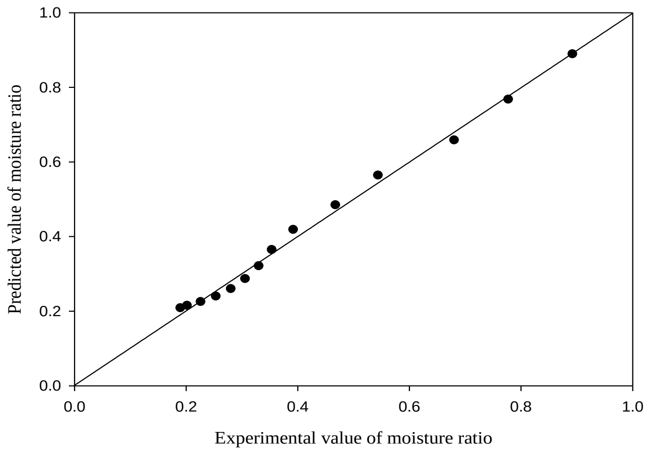

Fig. 5. Comparison between experimental moisture ratios (MR) and that predicted for Nerium Oleander calculated using Midilli and Kucuk model.

IV. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

The ISD implementing PCM is experimentally tested for drying Nerium Oleander. From the experimental obtained results it is concluded that the utilization of PCM in the ISD smoothes the temperature of dying air and provide a suitable temperature for drying Nerium Oleander during 14 hrs. It is inferred that using high thermal conductive particles with paraffin wax as energy storage material may improve the thermal performance of the indirect solar dryer.

NOMENCLATURE

I the global solar radiation on a (30^o) tilted surface (W/m^2)
ISD indirect solar dryer
L latent heat of water (kJ/kg)
M_{od} initial moisture content on dry base
M_{ow} initial moisture content on wet base
M_f final moisture content
M_{td} instantaneous moisture content on dry base
M_{tw} instantaneous moisture content on wet base
$\dot{m}$ mass flow rate of air (kg/s)
m_o initial mass of the sample (kg)
m_d mass of the dried sample (kg)
m_t mass of the sample at any time (kg)
m_e mass of water evaporated (kg)
PCM phase change material
SR shrinkage ratio (dimensionless)
T_a ambient temperature (℃)
$T_{da(av)}$ average temperature of drying air (℃)
$T_{da(i)}$ temperature of drying air at the entrance of the drying compartment (℃)
t drying time (s)

Subscripts:
av average
d drying
i inlet
o outlet
th thermal

Greek:
η efficiency (dimensionless)

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