PERFORMANCE OF A DESICCANT ASSISTED PACKED BED PASSIVE SOLAR DRYER FOR COPRA PROCESSING

by

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In this paper, the performance of a novel desiccant assisted packed bed passive solar dryer was evaluated for copra processing and compared with conventional passive solar dryer. This novel solar dryer consists of a desiccant assisted packed bed solar air heater attached with a dryer cabin. The desiccant and phase change materials packed in the solar air heater has control the humidity and retains the heat for longer duration, respectively. The performance of the dryer was evaluated (in terms of drying time to attain the final equilibrium moisture content, drying rate, specific moisture extraction rate, pick-up efficiency, and dryer efficiency) under the meteorological conditions of Coimbatore city in India during March and April 2016. The copra was dried from initial moisture content (wet basis) of about 52% to the final moisture content (wet basis) of about 8% in 62 hours with specific moisture extraction rate of 0.82 kg/kWh. The drying time was reduced by about 44 hours when compared to the conventional passive solar dryer. The dryer pick-up efficiency was varied between about 10% and 65%. The average dryer thermal efficiency was calculated to be about 32%. The quality of final dried product was found to be good.

Key words: packed bed desiccant passive solar dryer, copra processing

Introduction

India is the third largest coconut producing country in the world. Copra is one of the major by-product processed from coconuts by reducing its moisture content to about 7% (by drying) to concentrate the oil content [1]. In India, the traditional methods adopted for copra processing are: open sun drying, kiln drying, and green-house dryer. The quality of copra obtained through open sun drying is poor due to the direct exposure of the product to the ambient [2]. Similarly, the kiln dryers have produced poor quality copra due to the direct exposure to the smoke [3]. In the case of green-house dryer, the drying time to reduce the final moisture content of about 7% is about 70 hours with a minimum batch capacity of 1000 coconuts [4]. The solar green-house dryers are not suitable for small holders producing less than 500 coconuts per batch. Moreover, the moisture gets absorbed back by the product during night hours in the major drawback. The heat pump dryer is another option producing high quality copra in with reduced drying time of about 40 hours [5, 6]. But, the processing cost using heat pump dryers is high. Many solar dryer configurations have been developed for processing the agricultural ma-

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terials [7, 8]. However, limited scope of applications for copra processing was reported. Mohanraj and Chandrasekar have attempted with FCSD using sand as sensible heat storage materials for processing copra under the climatic conditions of Pollachi (see in [9]). The moisture content on wet basis (w. b.) was reduced from about 52% to about 8% in 80 hours. The quality of copra obtained in solar dryers was found to be higher when compared to open sun drying. The cited literature confirmed that, many research investigations have been reported on solar dryers. However, the possibility of using packed bed absorber plate (for heat storage) and desiccant materials (to control the humidity at dryer inlet) hybrid passive solar dryer was not reported in open literature for copra processing. Hence, an attempt has been made in this work to evaluate the performance of a novel solar dryer configuration for copra processing. The drying characteristics of copra and energy performance of a novel passive solar dryer are investigated.

Experiments

The experiments were carried out in a forced convection passive solar dryer under Coimbatore climatic conditions (latitude of 10.98° N and longitude of 76.96° E) during 2015.

Experimental set-up

The passive solar drier (fig. 1) consists of a packed bed flat plate solar air heater of area 2 m^2 connected with a drying chamber of dimensions 1.5 × 1 × 1 m with a total volume of 1.5 m^3. The packed bed solar air heater has a copper absorber plate of 1.2 mm thickness coated with black paint to absorb the incident solar radiation. The heat loss through the back side of the air heater has been reduced by insulating the bottom surface of the absorber plate with 50 mm thick glass wool insulation. The top portion of the solar air heater was covered with a tempered glass of 5 mm thickness by maintaining a gap of 40 mm for air circulation. The air gets heated in the gap due to greenhouse effect. The top surface of the absorber plate has provision for holding 15 kg of paraffin wax to harvest the solar energy effectively and retains in absorber plate and maintains the consistent temperature even during fluctuations in solar irradiation and during off sunshine hours also. One side of the packed bed solar air heater was connected to the dryer with the help of reducer. The desiccant material was packed at the air heater outlet to control the relative humidity at the entry of the dryer. A drying chamber with 1.5 × 1 × 1 m was fabricated from mild steel plate of 20 gauge thicknesses. The dryer cabin is insulated with 10 mm of glass wool insulation to reduce the heat leakage from the cabin. The solar air heater was tilted to an angle of 20° with respect to horizontal, which is the optimum tilt angle for the metheorological conditions of Coimbatore. The air heater is oriented towards south to maximize the absorption of solar radiation incident on the solar air heater.

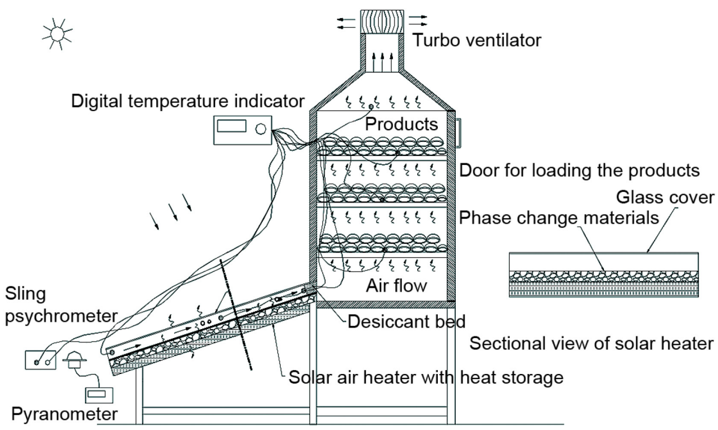

Figure 1. Schematic of desiccant assisted packed bed solar dryer

Instrumentation

Eight thermocouples (K type) were fixed at different locations of the solar air heater and dryer cabin to measure the temperature of the drying air. The thermocouples are connected with digital scanner having 0.1 °C resolution connected with rotary selector switch. Solar irradiation was measured with the help of pyranometer. Ambient wind velocity was measured using cup type anemometer. The relative humidity of air at dryer inlet and outlet were measured using sling psychrometer (having two thermometers one covered with wetted cloth and one with bare bulb). Based on the measured dry and wet bulb temperatures, the relative humidity was measured using psychrometric chart. An U-tube manometer along with orifice meter was fixed at the solar air heater outlet in the path of air circuit to measure the air flow rate entering the drier. A digital electronic balance of 1 kg capacity having an accuracy of ±0.001 g was used to weigh the drying samples. The accuracies of measuring instruments are listed in tab. 1.

Table 1. Specifications of measuring instruments

Instrumentation	Specification/Range	Accuracy
Temperature sensor	PT 100/0-200 °C	±0.2 °C
Pyranometer	Class-A/0-1500 W/m^2	±5 W m^{-2}
Anemometer	Cup type/0-15 m/s	±0.2 ms^{-1}
Sling psychrometer	Thermometers (0-100 °C)	±3%
Thermometer	Mercury (0-100 °C)	±0.2 °C

Experimental procedure

About three hundred and fifty coconuts were selected for one batch. The selected coconuts were broken into two halves and loaded over the trays (with 90% porosity) of the dryer cabin. During experiments, the temperatures at typical locations in the air heater and dryer chamber, solar irradiation falls on solar air heater, wind velocity, and relative humidity were measured at every one hour interval. The moisture content of the copra was measured once per hour. After attaining about 40% of the moisture content, the copra kernels were scooped from the shells and dried further to attain the final equilibrium moisture content of 7%. At the end of drying processes, the quality of copra was graded according to BIS 6220-1971 (mentioned in tab. 2) by selecting 100 cups randomly. Five trial experiments have been conducted in a conventional forced circulation solar dryer (FCSD) and desiccant assisted packed bed solar dryer. The experimental procedure was repeated for all the drying modes. But, the drying characteristics observed under similar ambient conditions were considered for performance comparison.

Table 2. Grading of copra BIS: 6220-1971

Characteristic [%]	Requirements		
	MC Grade 1	MC Grade 2	MC Grade 3
Impurities, by mass	0.5	1	2
Mouldy cups, by count	4	8	10
Black cups, by count	5	10	15
Wrinkled cups, by count	5	10	15
Chips, by mass	5	10	15
Moisture content, by mass	6	6	6
Oil content, by mass	70	68	68
Acid value of extracted oil	2	4	10

Data analysis

Drying characterstics

During experiments, five samples with 10 ± 1 g were chopped from randomly selected cups inside the dryer cabin for measuring the moisture content of the copra. The chopped samples were kept in a convective oven by maintaining the temperature in the range between 105 ± 1 °C for the period of about four hours. The moisture content was calculated based on the measured initial and final mass of the product. The moisture content on wet basis is:

$$M_{\mathrm{wb}} = \frac{m_{\mathrm{i}} - m_{\mathrm{f}}}{m_{\mathrm{i}}} \tag{1}$$

Further, the drying rate of copra is calculated using equation:

$$DR = \frac{\mathrm{d}M}{\mathrm{d}t} = -k(M_{\mathrm{t}} - M_{\mathrm{e}}) \tag{2}$$

The equilibrium moisture level is the safe moisture level in the product, up to which the moisture in the produce can be removed. At equilibrium moisture content, the vapor pressure exerted by the moisture within the product is equal to the vapor pressure of ambient air. The equilibrium moisture content of copra was experimentally measured as 7%. The moisture ratio is:

$$MR = \frac{M - M_{\mathrm{e}}}{M_{\mathrm{i}} - M_{\mathrm{e}}} \tag{3}$$

Performance characteristics

The pick-up efficiency of the dryer is used to evaluate the potential of the dryer to take-up the moisture from the products [10]. It is defined as the ratio between the mass of moisture absorbed through the drying chamber to the theoretical capacity of air to absorb the moisture from the products. It is given by:

$$\eta_{\mathrm{p}} = \frac{W_o - W_{\mathrm{t}}}{mt(H_s - H_{\mathrm{i}})} \tag{4}$$

The dryer thermal efficiency is the ratio between the mass of moisture evaporated to the amount of energy absorbed for evaporation [10]. It is given by:

$$\eta_{\mathrm{the}} = \frac{m_{\mathrm{evap}} h_{fg}}{\dot{m}_{\mathrm{a}} c_{pa}(T_2 - T_1) + m_{\mathrm{pcm}}(T_{\mathrm{i}-l} - T_{\mathrm{f}-l}) + m_{\mathrm{pcm}} h_{fg(\mathrm{pcm})} + m_{\mathrm{pcm}}(T_{\mathrm{i}-s} - T_{\mathrm{f}-s})} \tag{5}$$

The specific moisture extraction rate (SMER) is defined as the ratio between the amount of moisture extracted per unit energy absorbed by the dryer. The SMER is used to predict the effectiveness of the drying system. It is given by:

$$SMER = \frac{m_{\mathrm{evap}}}{E_{\mathrm{absorbed}}} \tag{6}$$

Uncertaininty analysis

The accuracy of measuring instruments will influence the accuracy of calculated results. The uncertainties in experiments are calculated using following equation given by Holman [11]:

$$w_r = \sqrt{\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \ldots + \left(\frac{\partial R}{\partial x_n} w_n\right)^2} \tag{7}$$

where, R is a given function, w_r – the total uncertainty, $x_1, x_2,\ldots, x_n$ are the independent variables, and $w_1, w_2,\ldots, w_n$ – the uncertainty in the independent variables. The uncertainties in calculated parameters such as, moisture content, drying rate, pick-up efficiency, and drying efficiency were calculated as ±3.2%, ±3.8% and ±3.5%, respectively.

Results and discussion

The experimental results obtained in a desiccant assisted packed bed solar dryer (observed on September 21, 2016) are compared with the results obtained from conventional solar dryer (observed on October 23, 2016). Five experimental trials were observed in each dryer. The observations made on similar ambient variations were considered for performance comparison.

Experimental observations

The variation of solar irradiation observed during experimentation with conventional solar dryer and desiccant assisted packed bed dryer are shown in fig. 2. The solar irradiation was varied from about 100 W/m^2 to about 930 W/m^2 during experimentation with both the dryers. The difference in solar irradiation observed during experimentation was found to be within 50 W/m^2. As expected, the solar irradiation gets increased during morning hours and gets reduced in the evening hours. The potential sunshine availability is about 8 hours per day. In fig. 3, the variations of ambient temperatures during experimentation are depicted. The ambient temperature was varied between 29 and 38 °C. The difference in ambient air temperatures during experimental observation were within 0.5 °C. The wind velocity variations are shown in fig. 4. The wind velocity was varied in the range between 0.9 and 3 m/s during experimentation. Similar wind velocity variations were observed during experimentation. Temperature variations observed at the dryer inlet are depicted in fig. 5. Air temperature at the dryer inlet was observed to be 2-3 °C higher in the case of desiccant assisted packed bed passive solar dryer when compared to the conventional solar dryer. Moreover five hours additional heat storage with humidity control options are possible in the case of desiccant assisted packed bed passive solar dryer.

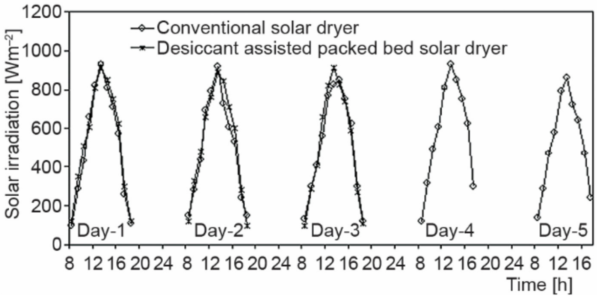

Figure 2. Variation of solar irradiation

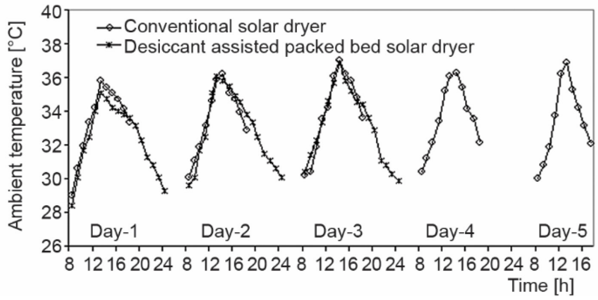

Figure 3. Variation of ambient temperature

Drying characteristics

The moisture content (w. b.) variations observed in experiments are illustrated in fig. 6(a). The moisture content (w. b.) of the copra was varied from the initial moisture content of

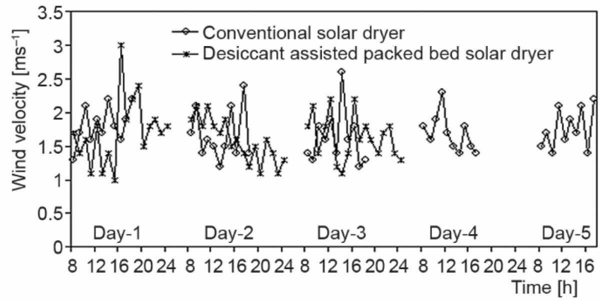

Figure 4. Variation of wind velocity

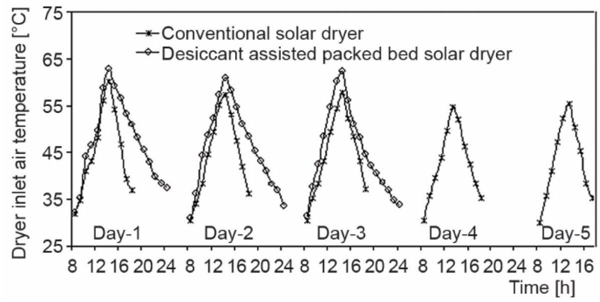

Figure 5. Variation of air temperature at dryer inlet

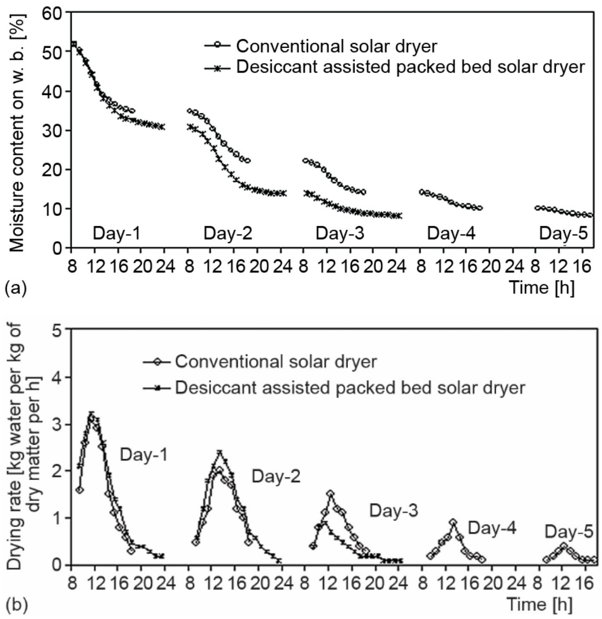

Figure 6. Drying characterstics of copra in a passive solar dryer; (a) variation of moisture content, (b) variation of drying rate

about 52% to final moisture content (w. b.) of about 8% in 62 hours using a novel desiccant assisted packed bed solar dryer. Whereas, the drying time in a conventional solar dryer was observed to be about 104 hours. The drying time was reduced by about 42 hours in the case of novel desiccant assisted packed bed passive solar dryer when compared to conventional solar dryer. The packed bed dryer has potential to harvest the solar energy effectively and retains the heat in the absorber plate. The absorbed heat is released during off sunshine hours and maintains higher air temperature inside the dryer cabin for about 6 hours additionally. The drying rate during initial stages of drying was found to be higher due to the evaporation of free moisture available on the surface of the product. The variation of drying rate is illustrated in fig. 6b. A maximum drying rate of about 3.5 kg/kg of dry matter was observed in the case of desiccant assisted packed bed dryer, which was found to be higher when compared to the conventions solar dryer, which was about 3.2 kg/kg of dry matter. The drying rate starts with constant rate period initially and changes to falling rate period subsequently. In the case of constant rate period, the moisture removal was taking place from the surface of the product due to evaporation of free moisture at the surface. The variation of moisture ratio is illustrated in fig. 7. The moisture ratio gets reduced from 1 to final moisture ratio of 0.02.

Performance of the dryer

At the end of drying processes, about 56 kg of moisture content was removed from 350 coconuts to obtain 68 kg of dried copra in one batch. The specific moisture extraction rate of the desiccant assisted packed bed solar dryer and conventional solar dryer are 0.82 kg/kWh and 0.64 kg/kWh, respectively, at constant air mass flow rate of 0.01 ± 0.001 kg/s. The maximum pick-up efficiency of about 38% was observed during peak sunshine hours in the case of conventional passive solar dryer. Whereas, the maximum pick-up efficiency of about 65% was observed in the case of desiccant assisted packed bed passive solar dryer. The maximum pick-up efficiency was observed in both the dryers during initial states of drying due to absorption of free moisture from the surface layers. The pick-up efficiency was also influenced by desiccant packed at the outlet of the solar air heater. The pick-up efficiency was reduced to about 10% during final stages of drying due to the reduced moisture content in the product. The average dryer thermal efficiency was calculated to be about 26 and 32% for the case of conventional passive solar dryer and desiccant assisted packed bed passive solar dryer. High dryer thermal efficiency was observed during initial stages of drying and gets reduced during latter stages.

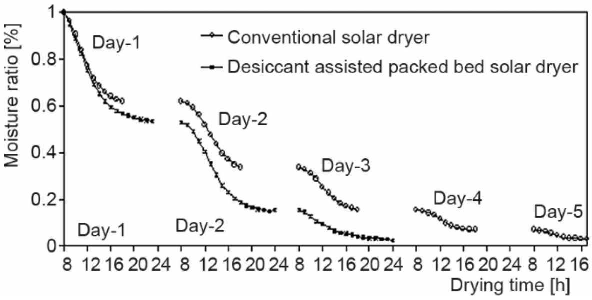

Figure 7. Variation of moisture ratio with drying time

Quality of the product

The quality of copra obtained are graded as 78% milling copra grade-1, 16% milling copra grade-2, and 6% milling copra grade-3. The quality of copra obtained was found to be good compared to other drying methods such as sun drying and kiln drying. The investigations confirmed that desiccant assisted forced convection passive solar dryer is more suitable for small scale copra processing in remote locations without electricity.

Conclusions

The performance of the novel configuration solar dryer was evaluated for copra drying. The following conclusions were drawn from this investigation.

- The initial moisture content (w. b.) of the copra was reduced from about 52% to the final moisture content (w. b.) of about 8% in 62 hours duration, which is found to be lesser when compared to conventional solar dryer, which has about 104 hours.
- The packed bed absorber plate configuration has capable of retaining the heat for about five hours additionally, which increases the drying duration.
- The desiccant packed at the air heater outlet has reduced the relative humidity at the dryer inlet. The reduction in relative humidity has enhanced the dryer pick-up efficiency.
- The maximum pick-up efficiency of about 65% was observed during peak sunshine hours (initial stages of drying) in the case of desiccant assisted packed bed passive solar dryer.
- The average dryer efficiency was calculated as 26 and 32% for the case of conventional solar dryer and desiccant assisted packed bed passive solar dryer, respectively.
- The SMER of the desiccant assisted packed bed passive solar dryer was found to be 20% higher when compared to conventional solar dryer.
- About 80% of high quality copra was obtained in the novel desiccant assisted packed bed passive solar dryer.

The investigations confirmed that desiccant assisted packed bed passive solar dryer is more economical option for small scale copra processing.

Nomenclature

A – area of the solar air heater, [m^2]
c_p – specific heat, [kJkg^{-1}K^{-1}]
E – energy absorbed by the dryer, [W]
h_{fg} – latent heat of evaporation, [kJkg^{-1}K^{-1}]
I – solar irradiation, [Wm^{-2}]
k – drying constant
M – moisture content on wet basis, [%]
M_e – equilibrium moisture content, [%]
M_i – initial moisture content, [%]
M_t – moisture content on (w. b.) at time t, [%]
$\dot{m}_a$ – mass flow rate of air, [kgs^{-1}]
m_{evap} – mass of moisture evaporated, [kg]
m_f – final mass of the product, [g]
m_i – initial mass of the product, [g]
m_{pcm} – mass of phase change material, [kg]
T – temperature, [°C]
T_1 – air temperature at dryer inlet, [°C]
T_2 – air temperature at dryer outlet, [°C]
$T_{f\text{-}l}$ – final temperature of liquid PCM, [°C]
$T_{f\text{-}s}$ – final temperature of solid PCM, [°C]
$T_{i\text{-}l}$ – initial temperature of liquid PCM, [°C]
$T_{i\text{-}s}$ – initial temperature of solid PCM, [°C]
t – time, [s]

Greek symbols

η_p – pick-up efficiency, [%]
η_{the} – dryer thermal efficiency, [%]

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