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Solar dryer using evacuated tube solar thermal collector with thermal storage

T H BIDYALAKSHMI DEVI[1]*, S K SINGH[2], INDRA MANI[3], S KUMAR[2], V YADAV[2], Y SINGH[2] and SUNIL K SANGWAN[2]

National Institute of Solar Energy, Gurugram, Haryana 122 003, India

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Drying protects the high-moisture food from microbial attack but drying temperature should not impact the product quality. Drying of the produce at 40–60ºC keeps the nutrients content intact (Kant *et al.* 2016). Open-air drying is easiest, cheapest and most popular. Although sun drying is cheap but weather, product damage and long drying durations are some consequences (Jairaj *et al.* 2009). Solar drying solves the problems associated with the sun drying. Low and medium temperature solar water heaters, air warmers, cookers, and dryers are 40–60% efficient. Although monocrystalline silicon-based modules offer 20% efficiency, solar PV production prices have dropped due to widespread use. Reflection losses are higher than the vacuum tube thermal heat collectors and hence the collector efficiency is less. Sundari *et al.* (2013) found that solar evacuated tube collectors has better performance than the flat plate collector. Thus, hybrid heat-electricity systems will provide better output than using SPV or solar thermal system alone for drying.

Phase change materials (PCM) can maintain a mild, steady temperature for drying most agricultural goods (Shalaby *et al.* 2014). It can maintain the temperature of 40–75ºC and hence reduce the energy required for drying. Paraffin wax as PCM can maintain 6–9ºC above ambient temperature in a portable forced convection solar dryer for chilies after 6–7 h of sunshine (Vaibhav *et al.* 2016).

Ginger has anti-inflammatory, anti-emetic, anti-viral, anti-motion, anti-nauseant and chemoprotective properties. It's initial moisture content ranges from 80–90% (w.b.) which need to reduce below 10% for safe storage. With the aim to bring sustainable development in agricultural processing sectors especially drying, a study was carried out to develop solar dryer for drying ginger.

Design of the dryer: An experiment was conducted at National Institute of Solar Energy, Gurugram, Haryana during 2018 for development of solar dryer. The dryer was designed for uniform drying of ginger. It was powered entirely by the solar energy using both thermal and electrical effects. The thermal power was obtained through heat pipes connected in series in a header pipe. One end of header pipe was connected with DC fan while the other end was connected with the drying chamber. The fan was powered by SPV panel.

Determination of design values: The quantity of moisture to be removed depends on crop, harvest moisture, total solar energy received in the location and design. The mass of ginger to be dried and the heat needed to evaporate the moisture determined the energy require to dry it.

Drying load estimation

a) The amount of moisture to be removed from the product, m_w (kg) was determined using the following equation (Tonui *et al.* 2014).

$$m_w = m_p \frac{(m_i - m_f)}{(100 - m_f)} \quad (1)$$

b) The quantity of heat required to remove the moisture content was determined using equation (2) (Hussein *et al.* 2017).

$$Q=m_p C_p \Delta T_p + m_w h_{fg} \quad (2)$$

C_p, Specific heat of product (Sahay and Singh 2004)

$$c_p = \left(\frac{m_w}{100}\right) \times c_w + \frac{(100 - m_w)}{100} \times c_d$$

C_w, specific heat of water, 4.18 kJ/kg K

C_d, specific heat of dry matter, 1.463-1.881 kJ/kg K

ΔT_p, change in temperature before and after heating, t_a-t_p, ºC

Therefore, C_p=2.0 kJ/kg K

The amount of heat required is the function of temperature and moisture content of crop. The latent heat of vaporization was determined as (Dasin *et al.* 2015):

$$h_{fg} = 4.186(597 - 0.56(t_{pr}+273)) \quad (3)$$

[1]ICAR-Central Institute of Post-Harvest Engineering and Technology, Ludhiana, Punjab; [2]National Institute of Solar Energy, Gurugram, Haryana; [3]ICAR-Indian Agricultural Research Institute, New Delhi. *Corresponding author email: bidyala@gmail.com

where, t_{pr} [ºC] is the product temperature.

Design of drying chamber

Size, number of trays, tray spacing and insulation were drying chamber design features. The dryer's capacity was 5.0 kg with thin layers drying (1–2 mm). To use additional products from village sales, the dryer's capacity was kept low. Local wood was used for making the drying chamber. Aluminium sheet was bonded to 1.0 cm glass-wool to prevent chamber heat loss. The bottom chamber, also a plenum chamber, had a 28 cm height and an 8.5 cm diameter hole for hot air. The bottom chamber's aluminium pouch held PCM, using up the space. Table 1 shows the design parameters.

Number of trays

Numbers of trays were provided based on the capacity and permissible thickness of the ginger slices to be dried in thin layer drying. Perforated trays were selected to allow easy flow of the air. Area of tray was kept to fit inside chamber i.e. (0.52 m × 0.48 m = 0.25 m^2). The height of the tray was kept as 3.0 cm considering the thickness of layer and clearance for handling. The number of trays were seven and the first tray was used for storing PCM.

Dimension of outside chamber

The dimension of the outside chamber was determined by adding together the thickness of insulation and thickness of the wooden plank.

Length, $L= L_i+[(2\times1.5)+(1\times2)]= 60$ cm

Height, $H= H_i+[(2\times1.5)+(1\times2)]= 105$ cm

Width, $W=W_i+[(2\times1.5)+(1\times2)]= 55$ cm

An insulated door was provided to prevent heat loss and to make the chamber air-tight. Thus, the overall dimension of the drying chamber was 0.55 m × 0.50 m × 0.1 m.

Selection of Solar thermal collector

Based on the temperature requirement for drying (40–60ºC), the header pipe based evacuated tube solar collector was considered for design. All the heat pipes were connected to 7.6 cm diameter copper duct which was well insulated with glass-wool. Based on the preliminary study and the heat energy requirement, 24 heat pipes were selected. The gross area of the collector was 1.91 m × 1.65 m.

Air handling and distribution unit: The main parts of this unit included fan and air duct i.e. header pipe for forced air convection process. The dimension of the header pipe was 2.01 m × 0.23 m × 0.21 m. A SPV panel operated DC fan blew air to the drying chamber from an inlet pipe having diameter of 8.5 cm. Two thermometers were placed to record the temperature at entrance of hot air and exit of exhaust air. The schematic diagram of the developed solar dryer included drying chamber, evacuated tube thermal collector, fan and SPV (Fig 1).

Table 1 Design parameters

Parameter		Standard values/ assumptions/ Determined values
Initial moisture content of ginger	m_i	85–86% w.b.
Final moisture content	m_f	10–13% w.b.
Initial mass of the product	m_p	5.0kg
Initial temperature of product	t_p	25ºC
Specific heat of air	C_{pa}	1.005 kJ/kg K
Average Ambient temperature	T_a	24ºC
Density of air	ρ_a	1.225 kg/m^3
Length of inside chamber	L_i	55 cm
Width of inside chamber	W_i	50 cm
Height of inside chamber	H_i	100 cm
Latent Heat of vaporization	h_{fg}	1800.48 kJ/kg
Avg. global inclined radiation	GIR	650 W/m^2

Thermal storage unit: During the sunshine hours the heat was distributed to chamber for drying purpose as well as for charging PCM. Paraffin wax was used to store the thermal energy.

Considering 80% of heat energy required for drying is supplied during daytime and remaining 20% energy is to be stored for used in non-sunshine hours, the amount of paraffin required was calculated as:

$$\text{Amount of PCM} = \frac{\text{Amount of energy require to store}}{\text{Latent heat of storage}}$$

7915*0.2/174 =9.1 kg

PCM was filled at aluminum pouch having 500 g capacity and properly sealed package was then kept at plenum chamber near hot air inlet for charging. The properties of the selected paraffin wax used for thermal storage was studied. The thermal properties were studied using differential scanning calorimeter.

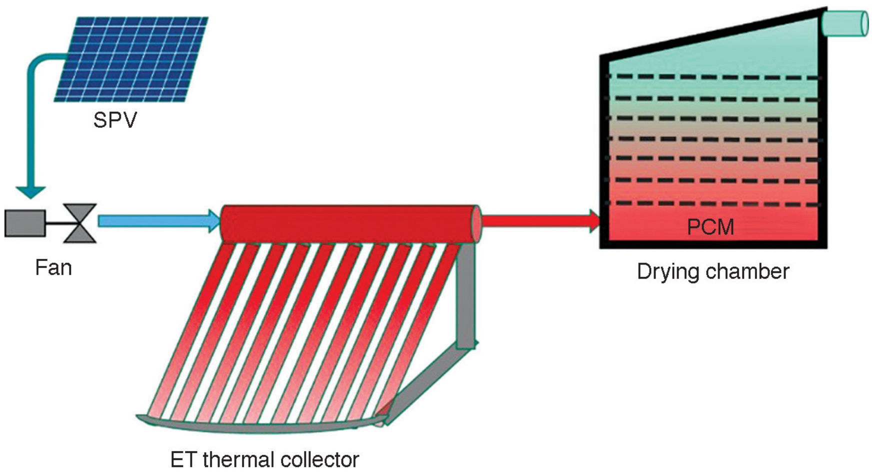

Fig 1 Schematic diagram of the developed solar dryer.

Performance evaluation of the dryer

a) System efficiency: The system efficiency can be defined as the ratio of energy required to evaporate the water plus sensible heat require to raise the temperature of the product to the useful energy gained from solar collector (Tonui *et al.* 2014).

$$\eta_{dryer} = \frac{m_p c_p \Delta T_p + m_w h_{fg}}{Q_a}$$

Where Q_a, total energy received by solar thermal collector.

b) Specific moisture extraction rate (SMER): SMER is defined as the amount of water evaporated per unit energy consumption in kg/kWh as given by Prakash and Kumar (2017).

$$\text{SMER} = \frac{\text{Mass of water removed (kg)}}{\text{Total energy consumption (kWh)}}$$

Total Energy consumption = Energy received from collector × Drying Time

The reciprocal of SMER gives the Specific energy consumption (SEC).

Estimation of total cost of construction

The total cost of construction of the dryer was evaluated by taking all the cost of the materials required in construction of the dryer.

The solar dryer was evaluated during January and February. Test conditions were bright and clear.The ginger's original moisture content was 85.8% w.b. It was dried to 12.81% w.b. The initial moisture in 5.0 kg ginger was 4.2 kg. The required heat energy was 7915 kJ to remove 4.2 kg of moisture.

The dryer used solar thermal and electrical power. Latent heat from paraffin wax (PCM) was stored during the day. Drying and charging PCM were done using solar heat. Low radiation discharges the PCM. Based on capacity and energy needed to remove moisture to acceptable levels, design values were determined. The collector collected more heat and the fan speed rose as the solar panel received more energy at increasing ambient temperature. Depending on radiation, the drying chamber can reach 45–60ºC. Similarly, temperature range was obtained by Rajagopal *et al.* (2014). The specification of the dryer is shown in Table 2.

Properties of paraffin wax: The melting of paraffin wax started at 58.3°C and completed at 60.7°C. The latent heat melting of paraffin wax ranged between 172.4 to 176.5 J/g. The specific heat and thermal conductivity were 2.14 kJ/kg K and 0.25W/m K respectively.

Performance of the developed dryer: The ratio of dryer heat used to air heat provided is called dryer efficiency. Dryer efficiency was 27% during testing. This thermal efficiency is comparable to solar dryers using air-based solar collector systems that dry chilli (28%) and jackfruit leather (33%), (Fudholi *et al.* 2015).

The specific moisture extraction rate was obtained as 0.514 kg/kWh whereas the specific energy consumption was 1.95 kWh/kg.

The total cost of dryer including labour charge was approximately ₹45,000.

Table 2 Specifications of developed dryer

Parameter	Value
Capacity of the dryer	5.0 kg
DC Fan rating	24V, 208 mA
Flow rate of air	0.048 m^3/s
Number of heat tubes	24 (dia-5.8 cm, length-165 cm)
Collector area	191 cm × 165 cm
Aperture area/observer area	(0.058 × 1.65 × 24)=2.34 m^2
SPV rating	24V
Inside chamber dimension	55 cm × 50 cm × 100 cm
Outside chamber dimension	60 cm × 55 cm × 105 cm
Header dimensions	2.01 m × 0.23 m × 0.21 m
No. of trays	7.0
Dimensions of tray	52 cm × 48 cm × 3 cm
Diameter of hot air inlet pipe	8.5 cm
PCM	Paraffin wax (58ºC)
Energy supplied by collector, Q_c	454.08 W
Efficiency of the dryer	26.9% (approx.27%)

Drying kinetics of ginger slice

The performance of the dryer was evaluated using ginger slices of 5.0 kg. Different drying curves i.e. moisture content vs drying time (Fig 2) and drying rate vs drying time (Fig 3) were plotted. Fig 2 demonstrates that drying reduced the moisture. The first day of drying was practically continual. Heat release from PCM may explain the moisture content drop from 78.69 to 76.3% (Fig 2). On the second day, drying rate started declining from 76.3% w.b. moisture content in the fourth hour. Thus, it lowered the load between the first and second drying days, helping energy sustainability (Kant *et al.* 2016). Between days 2 and 3, PCM reduced moisture by 3.31% w.b. Drying took 18 h to reach 12.8% w.b. Sansaniwal *et al.* (2017) found that the solar dryer could remove more than 70% moisture from onion (88.5 to 10.3%), ginger (55.8 to 15.7%), and

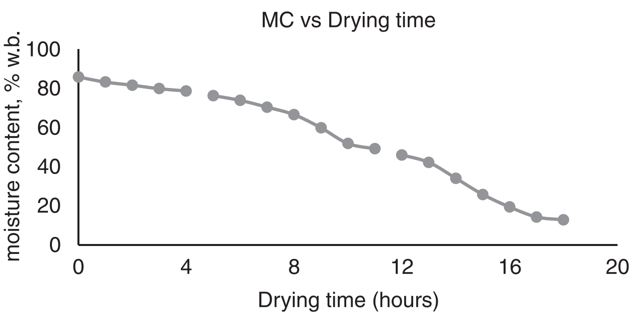

Fig 2 Variation of moisture content with time.

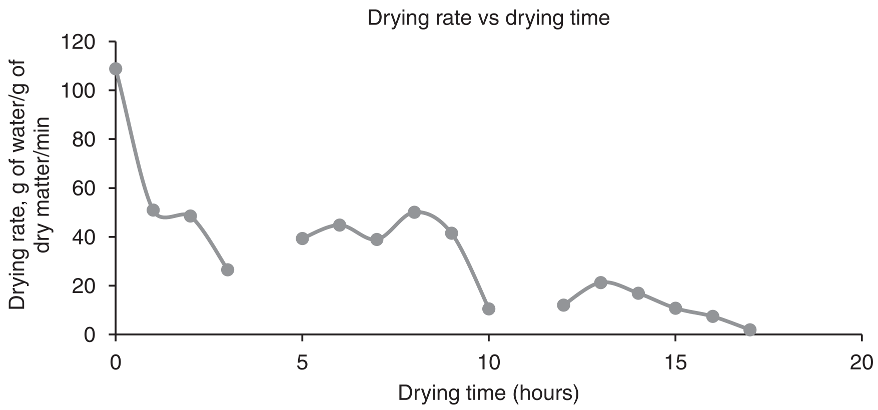

Fig 3 Variation of drying rate with drying time.

cabbage (72.5 to 15.0%) in 10 to 16 h, equivalent to the established dryer. However, Hoque *et al.* (2013) observed that mechanical tray dryers required 24 h to dry sliced ginger rhizomes from 84.97% (w.b.) to 8.59% (w.b.) at 60ºC and 28 h at 50ºC to achieve 14.62% (w.b.).

The drying rate curve shows water removal with time (Fig 3). Drying rates varied throughout 3 days. This showed product surface moisture removal. Due to lower morning radiation, drying rate was slower on the second and third days. Kagande *et al.* (2012) noticed drying rate inconsistencies between days. Drying rate reduced as moisture removal decreased. Peak radiation (1–3 pm) enhanced the drying rate again, removing the most moisture. When the solar rays dropped, drying slowed down again.

The capacity of the developed solar dryer for drying ginger is 5.0 kg. Solar thermal and electrical energy powered the dryer and it used local materials for construction. Use of PCM shortened drying time, stabilized temperature and kept the drying chamber warm, reducing thermal stress. Farmers can afford the ₹45,000 building cost. The dryer may help farmers save electricity and promote solar energy in agriculture.

SUMMARY

A solar dryer was developed using an evacuated tube solar thermal collector and solar photovoltaic (SPV) panel to supply the electrical energy. Paraffin wax was packed in a well-sealed aluminum package and stored in the bottom of the drying chamber near the entrance of hot air enabling recharge and store thermal energy. A DC fan was used to supply hot air to the drying chamber. The chamber was made of locally available material with glass wool as insulation. The overall dimensions were 0.6 m × 0.55 m × 1.05 m with 7.0 trays having 0.25 m^2 per tray. The capacity of the dryer is 5.0 kg. The maximum temperature that could attain inside the drying chamber during clear sunny days was 45 to 60ºC. The efficiency of the dryer is 27%.

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