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Performance studies on a forced convection solar dryer integrated with a paraffin wax–based latent heat storage system

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ABSTRACT

This manuscript presents the performance studies on a forced convection solar dryer integrated with a paraffin wax-based shell and tube latent heat storage unit. The solar dryer consists of two double-pass solar air heaters, a paraffin wax-based shell and tube latent heat storage module, a blower, and a drying chamber. The dryer was tested by drying 20 kg of red chilli in the drying air temperature range of 36–60 °C. The initial average moisture content of the chilli was 73.5% (w.b.) and was reduced to the final moisture content of 9.7% (w.b.) in 4 consecutive days. The dryer was operated daily for 10 h from 8:00 h to 18:00 h. The performance of each component of the drying system was evaluated using energy and exergy analyses. The average energy and exergy efficiency of the first solar heater were found to be 32.4% and 0.9%, respectively while for the second solar heater connected in the series with the first one were 14.1% and 0.8%, respectively. The energy and exergy efficiency of the latent heat storage unit were in the range of 43.6–49.8% and 18.3–20.5%, respectively. The exergy efficiency of the drying chamber was found to be between 24.6% and 98.1% with an average of 52.2%. The specific energy consumption of the chilli and the overall efficiency of the drying system were 6.8 kW h per kg of moisture and 10.8%, respectively. The electrical energy consumption of the dryer was 0.7 kW h per kg of moisture which was only 10.3% of the specific energy consumption of the chilli.

1. Introduction

Drying is one of the oldest techniques of preservation of food and agricultural products.

The main objective of drying is to reduce the moisture content to the safe storage level, at which the products can be stored for a longer period without any deterioration. The low moisture content prevents the growth of microorganisms such as moulds, bacteria, and yeasts, in the agriculture products and reduces the chemical reactions deteriorating quality of the products (Bahnasawy and Shenana, 2004). It also reduces the mass and volume of the products resulting in minimum packaging, storage, and transportation costs (Akpinar, 2006).

Drying is an energy intensive operation as the latent heat associated with the moisture content of the product is to be removed by supplying the hot air. Different sources of energy such as LPG, coal, biomass, and solar energy are used to supply the energy requirement for the drying operation. Solar energy is the most widely used renewable energy source in the drying process. It has been used by humankind for many decades. The traditional open sun drying is the largest application of solar energy, and it is a cheap drying technique. However, the longer drying time, contamination, difficulty in controlling the drying process, losses of the natural colours and minerals, losses of products due to insect, bird and adverse weather, large drying area requirement, and high labour cost are the major limitations associated with the open sun drying. All these limitations of the open sun drying led to the development of solar dryers. In the solar dryer, the product is dried in an enclosed space or a drying cabinet at an elevated temperature by the hot air produced in a device known as the solar air heater. It is an efficient drying process compared to the direct open sun drying. The product is dried at high temperature and low relative humidity in the solar dryer compared to the open sun drying for the same solar radiation intensity. The product can be dried in the solar dryer in the drying air temperature varying between 45 °C and 60 °C which is more suitable drying air temperature range for many agricultural products (Agrawal and Sarviya, 2016a). However, the intermittent nature and the uncertainty in the availability of the solar radiation are still the concerns associated with the solar dryer. These concerns affect the reliability of the solar dryer and thus limit the application. To overcome these challenges, auxiliary heat sources such as electrical heater, biomass

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Nomenclature

A	area (m^2)
c_{pa}	specific heat of air (J/kg-K)
$\dot{Ex}$	exergy (W)
Ex	net exergy (J)
g	acceleration due to gravity (m/s^2)
h	specific enthalpy (J/kg)
h_{fg}	specific enthalpy of evaporation (J/kg)
I	solar radiation intensity (W/m^2)
$\dot{m}_a$	mass flow rate of air (kg/s)
m_w	mass of moisture (kg)
m_p	mass of product (kg)
M_i	initial moisture content (w.b.)
M_f	final moisture content (w.b.)
P	pressure (bar)
p_t	total power (J)
p_{bl}	blower power (W)
$\dot{Q}$	heat transfer rate (W)
Q	heat transfer (J)
R	gas constant (J/kg-K)
SEC	specific energy consumption (kW h/kg)
t_d	total drying time (s)
t	time (s)
T	temperature (K)
v	velocity (m/s)
$\dot{W}$	work transfer (W)
Z	datum (m)

Greek symbols

α	absorptivity
τ	transmissivity
η	efficiency (%)

Subscripts

amb	ambient
ch	charging
d	dryer
dest	destruction
dich	discharge
ds	drying system
en	energy
es	energy storage
i	inlet
in	input
ls	loss
o	outlet
r	reference
re	received
s	solar
SAH	solar air heater
SAH-1	solar air heater-1
SAH-2	solar air heater-2
u	useful

stove, and LPG stove are generally incorporated into the solar dryer. The solar dryer is also integrated with the thermal storage to supply the heat requirement for drying during the cloud cover or inadequate solar radiation period.

Usually, two types of thermal energy storage modules viz., sensible heat storage (SHS) and latent heat storage (LHS) are used in the solar dryer. In the sensible heat storage, the temperature of the storage materials such as stone, rock, concrete, pebbles, and water (Leon and Kumar, 2008; Madhlopa and Ngwalo, 2007; Aguilar-Castro et al., 2012) is raised to store the thermal energy. While in the latent heat storage, the phase change materials (PCM) such as paraffin wax (Esakkimuthu et al., 2013) and Calcium chloride hegzahydrat (Cakmak and Yildiz, 2011) are generally used. The thermal energy is stored by the transition of phase of the storage material from solid to liquid.

The application of LHS in the solar dryer has recently received much research attention due to many advantages associated with it such as high energy storage capacity, dissipation of the energy at near constant temperature, and low volume to mass ratio. Devahastin and Pitaksuriyarat (2005) investigated the feasibility of using a paraffin wax-based LHS unit in the solar dryer. The melting temperature of the wax employed in the storage was in the range of 35–54 °C. The authors studied the effect of the air velocity and the temperature on the charging and discharging characteristics of the PCM and reported that the charging time decreased with increase in the air temperature and the velocity. The drying rate of the sweet potato increased with decrease in the air velocity through the storage. This was due to the higher drying air temperature. At lower velocity, the air could extract more energy from the storage resulting in high temperature. They reported that the incorporation of the LHS helped in saving 34–40% energy during drying.

Shalaby and Bek (2014) designed an indirect - type forced convection solar dryer integrated with a LHS unit and tested the dryer with and without thermal storage for drying medicinal plants. Two vertical cylindrical containers filled with the paraffin wax of having melting temperature 49 °C and thirty - two copper tubes embedded uniformly (through which air is supplied) in the wax were used as the storage unit. The investigators reported that the accumulated heat released from the storage during discharge period maintained the drying air temperature higher than the ambient temperature by 2.5–7.5 °C for 5 h after the sunset. Shringi et al. (2014) developed a solar dryer coupled to a PCM - based energy storage unit and an evacuated tube heat - pipe collector. A working fluid of the mixture of 60% propylene glycol and 40% water was heated to 54–118 °C in the collector and then circulated through a heat exchanger coil located in the PCM (melting temperature of 87 °C) of the latent heat storage unit during the charging process. The heat retained in the PCM was recovered simultaneously by circulating air through another coil embedded in the PCM. Then the air at the temperature between 39 °C and 69 °C was used in the dryer for drying garlic cloves. The investigators reported that the exergy efficiency of the drying process was in the range of 5–55% in the first 3 h of the drying period without recirculation of the exhaust air. Thereafter, the exhaust air was recirculated in the dryer, and the exergy efficiency was in the range of 67–88%. Jain and Tewari (2015) developed a passive solar dryer integrated with a LHS storage unit and tested the dryer by drying mint. The energy storage unit consisted of 48 cylindrical tubes of 0.75 m in length and 0.05 m in diameter. The tubes were filled with 48 kg of paraffin wax and positioned at the bottom of the drying chamber just below the drying trays. For the natural draft system, the top of the drying chamber was fitted with a black absorber plate, and a toughen glass was placed above it. A packed bed of the PCM was placed below the absorber plate. The energy storage module supplied the drying air at a temperature of 6 °C higher than the ambient temperature for 5–6 h after the sunset. Agrawal and Sarviya (2016b) studied the heat transfer characteristics of a shell and tube