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Tomato slices drying in a liquid desiccant-assisted solar dryer coupled with a photovoltaic-thermal regeneration system

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ABSTRACT

A liquid desiccant-assisted solar dryer was developed for tomato slices drying. In this dryer a photovoltaic-thermal solar collector was used to supply the required electrical energy and regenerate the desiccant. Experimental analysis of the dryer indicated that electrical energy needed for tomato drying was ranged from 0.65 to 1.4 kW h. The maximum specific moisture extraction rate was around 0.275 kg/kW h. It was also revealed that both solar heat fraction and ratio of solar electricity to consumed electricity increased with decreasing the drying temperature. The designed dryer was able to supply the required electricity independent of grid with drying at the temperature of 60–65 °C and regeneration's pump activation relative humidity (RH) of 28%. Color analysis of the dried tomato indicated that the increase in the temperature of the drying air increased the lightness (L^*), and yellowness (b^*) values, but the increase in the RH decreased the values of lightness and redness (a^*). In addition, the hue angle values of dried tomatoes increased with increase of the activation RH and drying temperature, producing dry slices with slightly light red color. Based on the fair value of solar electricity generation and good color qualities of the final products, the temperature of 60 °C and activation RH of 23% was recommended for tomato slices drying in this dryer.

1. Introduction

Drying is the most common preservation technique used to extend the shelf-life of fresh vegetables and fruits as well as to facilitate their transportation and storage (Serhat Turgut et al., in press). Although water removal using the different drying methods inhibits microbial growth and enzymatic activity and reduces chemical changes in the dried products, but it is the most energy consuming process in food industry (Horuz et al., 2017). In this way, different designs of solar air collectors have been developed to improve the useful thermal energy gain from the solar radiations. Chamoli and Thakur (2014) and Chamoli (2015) have investigated V-down perforated baffles on the absorber plate of the solar air collectors. Bhowmik and Amin (2017) tried to improve thermal efficiency of the flat plate solar collectors using reflectors. Gawande et al. (2016) analyzed a solar air collector equipped with reverse L-shaped ribs and achieved a maximum Nusselt number enhancement of 282% over the smooth collector duct. Sawhney et al. (2017) experimentally investigated the performance characteristics of a solar collector with delta winglets. The study reported a maximum Nusselt number enhancement of 223% over the flat plate collector and a thermo-hydraulic performance of 2.09.

In hot air dryers, a large percentage of thermal energy is wasted via the exhaust air. Therefore, recycling the exhaust air can improve energy efficiency of the system. In this regard, a number of researchers have applied different methods of heat recovery to the conventional hot air dryers. Sarsavadia (2007) achieved an energy saving of 70.7% by partially recycling of the exhaust air in a solar-assisted forced-convection dryer. Also, Julklang and Golman (2015) presented a spray dryer with a waste heat recovery system through which the exhaust air was supplied to an air-to-air heat exchanger to preheat the drying air. Similar heat recovery system was used for convective-infrared drying of kiwifruit by Özdemir et al. (2017).

In dryers with the air recycling system, the hot air, after passing over the products, is re-circulated to the dryer to be heated again for contribution in drying process. The major drawback of this type of the dryers is the gradual decrease in the moisture absorption potential of the circulating air due to increase in its RH. To overcome this problem, desiccant beds (Chramsa-ard et al., 2013; De Antonellis et al., 2012; Misha et al., 2015) and heat-pumps (Aktaş et al., 2017, 2016; Ceylan and Gürel, 2016; Chapchaimoh et al., 2016) are commonly used to

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Nomenclature

a^*	redness
b^*	yellowness
C_{pa}	specific heat of drying air (J/kg °C)
DR	drying rate (kg/min)
dt	time interval of measurements (min)
E_{fan}	electrical energies consumed by blower (W h)
E_{heater}	electrical energy consumed by auxiliary heater (W h)
E_{pump}	electrical energies consumed by the pump (W h)
E_{pv}	electrical energy generated by PV module (W h)
E_{th}	thermal energy provided by solar collector (W h)
H°	hue angle
h_{ci}	inlet enthalpy of solar collector (J/kg)
h_{co}	outlet enthalpy of solar collector (J/kg)
L^*	lightness
$\dot{m}_a$	mass flow rate of drying air (kg/s)
m_{wd}	mass of the removed moisture (kg)
PV	photovoltaic
PV-T	photovoltaic-thermal
Q_c	rate of useful thermal energy gain of solar collector (W)
t	time of drying (min)
RH	relative humidity
W	product weight (kg)
SECE	solar electricity to consumed electricity
SF	solar fraction
SHF	solar heat fraction
SMER	specific moisture extraction rate (kg/W h)

remove the extra moisture from the drying air.

However, the desiccant materials have a limited water absorption capacity and their absorbing ability decreases with the increase in their moisture content. So, the desiccant regeneration, which is usually a time and energy-consuming process, is considered. Several researchers have integrated rotary desiccant wheels with solar dryers for continuous and energy efficient drying during the daily time. Kabeel and Abdelgaied (2016) have reported that drying time and quality of final products improved when using a rotary desiccant wheel with the solar dryer. The results also showed that the rotary desiccant increased the useful thermal energy gain of the solar dryer by 153%. The results of a study revealed that drying time decreased by 25% when using a rotary desiccant wheel with a hot air dryer. While, total energy consumption of the combined system was 40–80% higher than that without desiccant wheel (Madhiyanon et al., 2007).

Compared with solid desiccants, liquid desiccants can be regenerated at lower temperatures and have higher moisture removal capacities (Misha et al., 2012). For this reason, more methods, such as the low temperature solar collectors and unused thermal energies generated by the industrial processes, are applicable to regenerate the liquid desiccants. Furthermore, instead of Chlorofluorocarbons and Hydro-chlorofluorocarbons, in the vapor compression cooling systems of the heat pump dryers, the liquid desiccants are not harmful to the environment (Shukla and Modi, 2017). The survey of the literature revealed that the use of desiccant material in the dryers needs extra equipment and heating sources to regenerate the desiccant during the drying process. This means that a fraction of useful generated thermal energy, that could be used to enhance water removal rate, should be spent for desiccant regeneration. This study presents a new liquid desiccant-assisted solar dryer for tomato slices drying. In order to continuous drying and simultaneous regeneration of the desiccant, a PV-T solar collector was designed through which the liquid desiccant could absorb the adverse heat accumulated on the PV panel, passing over it. The literature review indicates that there is a lack of information about the integration of PV-T technology, as the regeneration system, with a similar compound solar dryer.

2. Material and methods

2.1. Experimental setup

A prototype of the designed liquid desiccant-assisted solar dryer is depicted in Fig. 1. The dryer was comprised of an indirect solar dryer, a liquid desiccant bed and a PV-T desiccant regeneration system. A perforated (with a porosity of 3%) cross-finned solar absorber with the surface area of 1.1 m^2 was used in the solar collector. More details of the solar collector and drying chamber have been discussed by Ziaforoughi and Esfahani (2016). A 12V-DC-powered blower was used to circulate the drying air through the dryer's components and the desiccant bed. Furthermore, an electrical heater with a nominal power of 1000 W was installed inside the drying chamber, before the product tray, to serve as the auxiliary heater.

The desiccant bed was a galvanized iron chamber with the dimensions of $0.2 \times 0.3 \times 0.5$ m. The mist exhaust air of the drying chamber passes over the desiccant bed where a part of its humidity was absorbed by the absorbent material. In this study calcium chloride solution (concentration of 30% by mass) was used as the liquid desiccant. The desiccant regeneration process, when was needed, carried out by the PV-T solar collector which was a free-flow type, allowing the liquid to uniformly flow over the PV panel surface. The PV panel, a 110 Wp mono-crystalline PV module (As 110, Arya solar Co., Iran), was selected to provide at least half of the total electricity required for the drying process at the temperature of 65 °C. A 12V-DC pump with a nominal power of 12 W was used to deliver the diluted absorbent solution to a distribution pipe, which was installed on the top of the PV panel. The distribution pipe feeds the liquid uniformly on the panel surface to freely flows downwards and be regenerated by absorbing the accumulated heat of the panel. The concentrated solution, afterwards, was conveyed to the desiccant chamber through the return pipe. When the RH of the drying air raised over the adjusted set point, a RH control unit activated the regeneration pump to re-concentrate the diluted absorbent solution. This enhanced the moisture absorption potential of the desiccant bed and led to a drop in RH of the drying air below the set point. A schematic of the process occurred in the designed dryer on the psychrometric chart was illustrated in Fig. 2. The process includes three stages: stage 1 (line 1–2), through which temperature of the drying air increases by moving along the solar collector and over the auxiliary heater. Absolute humidity of the air remains constant in this stage.

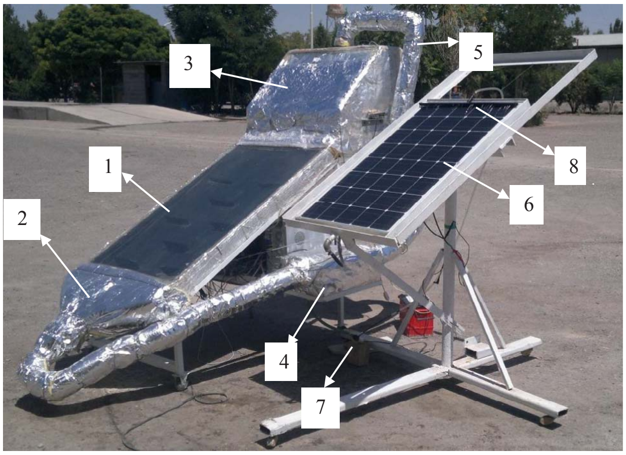

Fig. 1. A photograph of the liquid desiccant-assisted solar dryer: 1- solar collector, 2- air entrance to the collector, 3- drying chamber, 4- liquid desiccant bed, 5- connecting tube, 6- PV panel, 7- regeneration system's pump, 8- distribution pipe.