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Experimental investigation and thermodynamic performance analysis of a solar dryer using an evacuated-tube air collector

Chr. Lamnatou [a,*], E. Papanicolaou [a], V. Belessiotis [a], N. Kyriakis [b]

[a] Solar and Other Energy Systems Laboratory, National Center for Scientific Research "Demokritos", Aghia Paraskevi, 15310 Athens, Greece
[b] Mechanical Engineering Department, School of Engineering, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece

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ABSTRACT

The present work presents a thermodynamic performance analysis of a solar dryer with an evacuated-tube collector. Drying experiments for apples, carrots and apricots were conducted, after a preliminary stage of the investigation which included measurements for the determination of the collector efficiency. These results showed that the warm outlet air of the collector attains temperature levels suitable for drying of agricultural products without the need of preheating. Thus, the present collector was used as the heat source for a drying chamber in the frame of the development of a novel, convective, indirect solar dryer; given the fact that in the literature there are only a few studies about this type of collectors in conjunction with solar drying applications. Thin-layer drying models were fitted to the experimental drying curves, including the recent model of Diamante et al. [18] which showed good correlation coefficients for all the tested products. Drying parameters such as moisture ratio and drying rates were calculated. Furthermore, an energetic/exergetic analysis of the dryer was also conducted and performance coefficients such as pick-up and exergy efficiencies, energy utilization ratio, exergy losses were determined for several configurations such as single and double-trays and several drying air velocities. On the other hand, an optimal collector surface area study was conducted, based on laws for minimum entropy generation. Design parameters such as optimum collector area were determined based on the minimum entropy generation number. The mass flow number, along with the maximum collector and fluid exit temperatures were studied in relation to the minimum entropy generation. The energy/exergy analysis proposed, provides a useful tool for the evaluation of this type of collectors regarding their effectiveness as part of a solar drying system. Moreover, the results of the present study showed that the proposed solar dryer has a capacity for drying larger quantities of the products than those considered (in the frame of the experimental study) given the high efficiency of the collector. In general, the proposed system provides an interesting option for the penetration of this type of collectors in large-scale applications in the agricultural and industrial sector.

1. Introduction

Drying of agricultural products is an important post-harvest operation and since it requires high energy consumption, considerable energy savings can be achieved by using solar energy as energy source. Traditional sun drying has many disadvantages and thus drying by using a special device known as "solar dryer" is an attractive option. Solar dryers have been already applied in many countries [1] and extensive research has been carried out [2,3], aiming at the improvement of these systems. However, most of these studies regard solar dryers with flat-plate air collectors [4] and only a few of them considered a different type of collector [5]. Solar collectors with evacuated tubes (EVT) are a special type [6], offering significant advantages compared to flat-plate collectors, such as higher efficiencies [7]. EVT collectors, flat-plate ones alike, are classified into two broad categories, water- and air-collectors, based on their heat transfer fluid [6].

In the literature, there are several studies dealing with the thermodynamic performance analysis of solar and conventional drying systems. Some of these studies focus on the drying chamber, while others on the collector. In addition, some works carry out an energy/exergy analysis, while others are based on minimum entropy generation during thermal conversion of solar energy. Torres-Reyes et al. [8,9] developed a thermodynamic method for designing dryers operated by flat-plate solar collectors. A simplified method to design solar collectors based on the determination of minimum entropy generation during the thermal conversion of solar energy was proposed.

On the other hand, there are several studies which give emphasis on energy/exergy analysis of the drying chamber. Midilli and

* Corresponding author.
E-mail address: chryslam@eng.auth.gr (Chr. Lamnatou).

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Nomenclature

a, b, c, m	coefficients in the drying models
A_c	collection area of the solar collector (m^2)
A_p	plate area of the solar collector (m^2)
C_p	specific thermal capacity (kJ/(kg K))
DR	drying rate, DR = $(M_t–M_{t+\Delta t})/\Delta t$, (kg/(kg min))
G	solar radiation (W/m^2)
h	specific enthalpy (kJ/kg)
h_{as}	absolute humidity of the air entering the dryer at the point of adiabatic saturation (%)
h_i	absolute humidity of the air entering the drying chamber (%)
k, k_o, k_1	drying constants in drying models (h^{-1})
L	glass tube length (m)
$\dot{m}$	mass flow rate (kg/s)
M	moisture content (dry basis) at time t ($kg_{water}/kg_{dry.mater}$)
M_e	equilibrium moisture content (dry basis) ($kg_{water}/kg_{dry.mater}$)
MF	mass flow number
M_o	initial moisture content (dry basis) at time $t = 0$ ($kg_{water}/kg_{dry.mater}$)
MR	dimensionless moisture ratio = M/M_o
N_s	entropy generation number
R	glass tube radius (m)
S_{gen}	entropy generation rate (W/K)
T	temperature (K or °C)
t	time (h or s) or drying time (s)
T^*	reduced temperature, $T^* = (T_{in}–T_a)/G$ (m^2 K)/W
u	air velocity (m/s)
U_L	total heat loss coefficient (W/(m^2K))
$\dot{V}$	volumetric air flow rate (m^3/s)
W	weight of water evaporated from the product (kg)

Greek symbols

η_p	pick-up efficiency
θ	dimensionless temperature = T/T_a
θ'	dimensionless sun temperature = 6000 K/T_a
ρ	air density (kg/m^3)
$(\tau\alpha)$	transmittance-absorbance product

Subscripts

a	ambient
c	collector
dr	drying chamber
e	equilibrium
gen	generated
i	inlet
$init$	initial
L	loss
o	outlet
P	plate or pick-up
ref	characteristic value
S	entropy

Kucuk [10] conducted such an analysis of a solar drying system, whereby shelled and unshelled pistachios were studied. The results showed that the highest exergetic efficiency was obtained during shelled-pistachio drying. Akpinar [11] investigated the Thin-Layer Drying (TLD) characteristics of mint leaves in a solar dryer and under open-sun drying. Energy/exergy analysis was also performed. The results showed that the model of Wang and Singh [12] is the most suitable for describing the TLD behavior of mint leaves. In addition, the Energy Utilization Ratio (EUR) of the solar drying cabinet decreased with time, while the exergetic efficiency increased.

Akbulut and Durmus [13] studied the energy/exergy analysis of the TLD process of mulberry, via a forced solar dryer. EURs and exergetic efficiencies were determined. Both the EUR and exergy loss decreased with increasing drying mass flow rate, while the exergetic efficiency increased. Corzo et al. [14] conducted an energy/exergy analysis of TLD of coroba slices via a conventional, convective dryer. Both energy utilization and EUR increased with increasing drying time, while the exergy efficiency decreased.

In terms of TLD, in the literature there are several such studies for apple, carrot and apricot [15–17]. In the above mentioned references, TLD models such as those by Page, Newton, Henderson and Pabis, Midilli et al., the two-term and logarithmic ones etc., were fitted to the moisture content (MC) data of the products. In addition, Diamante et al. [18] fitted a new mathematical model on the TLD curves of fruits. TLD studies at different temperatures were carried out for kiwifruit and apricot. The new model was compared with the Henderson and Pabis, Page and logarithmic models. The proposed equation gave the highest coefficient of determination closely followed by the Page equation. However, it was pointed out that there is a need for further testing of this new model on several fruits.

In the frame of the present work, a novel solar dryer was developed and experiments were conducted on the EVT collector alone, as well as the entire drying system for apple, carrot and apricot TLD. A thermodynamic performance analysis of the dryer was conducted from energy and exergy point of view. In the literature there are several studies about energy/exergy analysis of solar dryers, however in the present work different agricultural products and different configurations such as single vs. double-tray, are examined. Optimal surface collector area study was also conducted based on the minimum entropy generation criterion and the results showed that energy/exergy analysis could be a useful tool during the study of this type of solar dryers. On the other hand, several TLD models were fitted to the products, including the new model of Diamante et al. [18] which showed good regression for all the tested samples.

Air solar collectors are appropriate for applications which require hot air for direct use, e.g. drying [19] which is the application of interest here as well. Since EVT air collectors are a promising new technology, there is a need for additional studies on this type of collectors and further penetration of them into other areas of application, including the agricultural sector. Thus, in the present work, a novel, experimental, indirect solar dryer was developed and tested, at the “Solar and other Energy Systems” Laboratory of NCSR “Demokritos” (Fig. 1) [20]. The solar heat needed for drying is provided by an EVT collector utilizing air as the working medium. At this point it should be mentioned that detailed numerical studies based on the above mentioned experimental set-up, have been conducted by the authors.

The findings of the present work can be valuable to researchers dealing with solar (and conventional) dryers design. Except of the scientific benefits, the present system also provides industrial benefits since the proposed configuration could also be utilized for the development of large-scale, industrial dryers. In general, the present EVT collector, due to its high performance, has the potential to be used for several industrial processes where high-temperature air is needed such as drying of timber [21]. Given the fact that EVT collectors are a promising solar thermal technology, the