Performance enhancement of a chimney operated passive solar dryer

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Abstract

This paper presents a performance evaluation of a passive solar dryer by a chimney effect experimentally. In this study, three different configurations of solar dryers have been proposed: two passive dryers (Case-1 and Case-2) and an active dryer (Case-3), one of the passive dryer with a chimney (Case-2) and the other without a chimney (Case-1). The energy and exergy efficiencies have been determined for the proposed solar dryers, and comparisons were made with one another. It also presents the effect of temperature rise and airflow rate. Thermocouples were placed to different locations along the solar dryer to collect temperature data for experimental analysis. The energy efficiency varied from 3% to 7% for Case-1, from 20% to 26% for Case-2, and from 21% to 42% for Case-3, while the exergy efficiency changed between 2% and 12% for all cases. The highest exergy efficiency was achieved by Case-1. The results revealed that a chimney dryer improved the airflow rate to a maximum of 0.71 $m.s^{-1}$ while a dryer without a chimney was 0.3 $m.s^{-1}$. Moreover, this paper found that energy efficiency increased with the airflow rate, whereas exergy efficiency decreased.

Key-words. Chimney effect, dryer, energy and exergy, solar air heater, solar radiation, temperature rise.

1. Introduction

Solar energy is fundamentally an inexhaustible source and capable of meeting some of the world's future energy needs. It is the most promising unconventional energy to contribute to low temperature applications like solar dryers and it is mainly dependent on location, availability of radiation, weather and time (Jain et al., 2017). Solar dryer is the oldest crop drying method that uses radiation from the sun as an input source. It is one of the energy intensive methods in which a large amount of energy is used to convert the moisture of the product into its vapour in the agricultural processing industry. The purpose of solar dryer is to reduce the water content of the products to the required moisture level to prevent the spoilage of the products (Belessiotis and Delyannis, 2011; El Hage et al., 2018).

The performance of solar dryers is determined by many factors such as the nature of dryers, intensity of solar radiation, ambient condition, drying rate, etc. (Mustayen et al., 2015). Solar dryers are broadly classified into natural convection dryers and forced convection dryers based on the mode of airflow. The air movement in natural convection is due to the buoyancy effect. This type of dryer normally operates inefficiently because the air circulation is poor (Ekechukwu and Norton, 1997). This results in higher temperature in the drying chamber which leads to burning of the product. The problem can be combated by using a properly designed chimney which can increase the air flow through the drying system (Habtay et al., 2019 and Afriyie et al., 2009).

The chimney effect has been studied in the past, but very few previous experiments have been considered in terms of enhanced convection. Senadeera and Kalugalage (2004) suggested that a chimney with polyethylene has a higher efficiency than the GI sheet metal chimney. In order to obtain a higher air flow rate in the drying system, the chimney should be heated so that mean air temperature in the chimney is higher than the ambient temperature. The effect of the chimney on the thermal performance of the solar air collectors has not been fully investigated experimentally.

Various researchers have experimentally performed exergy analysis of solar air collectors in addition to energy analysis (Benli, 2013; Esen, 2008). Exergy analysis estimates the efficient use of solar radiant energy and is used

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to improve the efficiency of a thermal system. Bouadila et al. (2014) studied the energy and exergy efficiency on solar air collectors experimentally using the equations of the first and second laws of thermodynamics. Their result showed that the daily average energy and exergy efficiencies were 40% and 22%, and it was also found that the collector outlet temperature is affected by the airflow velocity.

This study is concerned with investigating the effect of chimney on the thermal performance of the solar air collector of an indirect solar dryer experimentally under the no-load condition and using the equations of the first and second laws of thermodynamics. Three cases were tested in this study: Case-1: passive solar dryer without chimney; Case-2: same as Case-1 but with chimney; Case-3: active solar dryer. In addition, the comparison between a natural and an active solar dryer is investigated based on the presence of a chimney in a natural solar dryer.

2. Materials and Methods

The experimental study has been carried out in the Solar Laboratory of Szent István University, Gödöllő, Hungary. The latitude and longitude of the site are 47°35’24’’ N and 19°21’36’’ E, respectively. Solar insolation, ambient temperature, inlet airflow velocity, and temperatures at specific locations on the solar dryer were measured and recorded on 25 and 27 of September 2019. The duration of the measurement is from 10:00 to 15:00. The system has a height of 4.20 m and consists of a cylindrical chimney, a drying chamber, and a solar air collector. An appropriate chimney length has been considered to ensure thermally fully developed conditions at the chimney exit. The chimney was made up of plastic (PVC) pipe painted with matt black on its outer surface and installed at the exit end of the drying chamber. The characterization of the airflow inside the dryer included the determination of the meteorological and flow conditions.

2.1. Experiment set-up

The parameters to be measured for this study include collector inlet and outlet air temperatures, chimney outlet and ambient temperatures, airflow velocity at the collector inlet, and solar irradiation intensity on the collector surface. The experimental set-up is shown in Fig. 1.

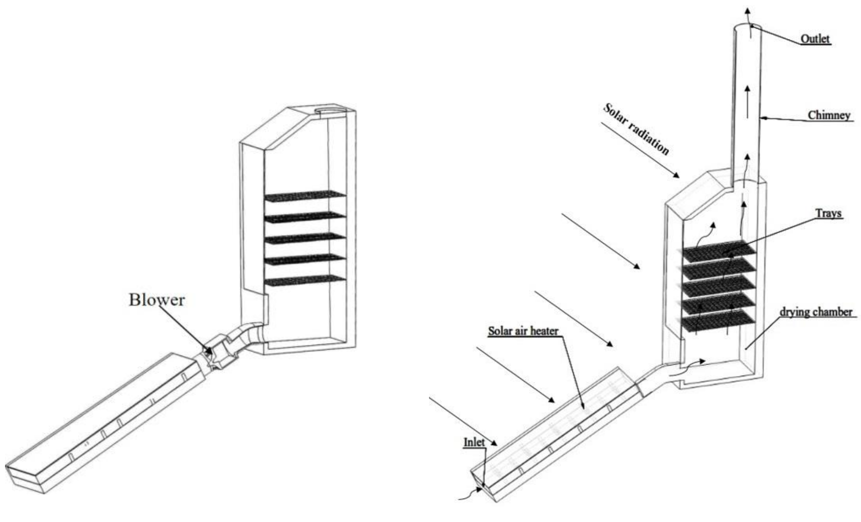


Fig. 1: Sectional view of a forced and natural convection solar dryers

The measuring devices used in this study are listed in Table 1. Temperatures were measured using the K-type thermocouple at different locations on the solar dryer. Each thermocouple was installed in the data logger and recorded automatically. The global solar radiation on the collector was measured using a pyranometer, with the sensor connected to the interface ADAMS 4018, which converts a digital signal in the data acquisition system. The air velocity at the collector inlet was measured using a digital handheld anemometer with an accuracy of ±0.3%.

Tab. 1: Apparatus used for data measurement

Instruments	Company, Country	Specification
Pyranometer	CM-11, Kipp & Zonen, Italy	Max: 4000 W m^{-2}
Thermocouple	8CH temperature data logger (KRIDA electronics), Latvia	-55 °C to 125 °C
Handheld anemometer	EC-MR 330 Eurochron GmbH, Germany	0 to 30 m s^{-2}

2.2. Energy and exergy analysis

The first and second laws of thermodynamics were used to investigate the energy and exergy efficiency of the solar air collector. The energy efficiency of the solar air collector is defined based on the first law of thermodynamics:

$$\eta_i = \frac{Q_u}{IA_c}. \qquad \text{(eq. 1)}$$

The useful energy gain for the presented system is calculated as follows:

$$Q_u = \dot{m}C_p(T_o - T_i), \qquad \text{(eq. 2)}$$

where,

Q_u (W) is the useful energy gain

I (W m^{-2}) is solar radiation intensity

A_c (m^2) is the collector area

$\dot{m}$ (kg.s^{-1}) is the mass flow rate at the collector inlet

C_p (J kg^{-1} K^{-1}) is the specific heat capacity of air

T_i and T_o (K) are the collector inlet and outlet air temperature

The exergy efficiency can be calculated on the basis of the second law of thermodynamics as the ratio of the exergy absorbed by the moving air to the exergy of the solar radiation on the collector:

$$\eta_{ii} = \frac{Ex_u}{Ex_{in}}. \qquad \text{(eq. 3)}$$

The useful exergy gain by air in the collector is defined as:

$$\mathrm{Ex_u} = \dot{m}\left[\mathrm{C_p}(\mathrm{T_o} - \mathrm{T_i}) - \mathrm{T_a}\left(\mathrm{C_v}\mathrm{Ln}\left(\frac{\mathrm{T_o}}{\mathrm{T_i}}\right) - \mathrm{RLn}\left(\frac{\rho_o}{\rho_i}\right)\right)\right] \qquad \text{(eq. 4)}$$

and the input exergy of the sun radiation is defined as (Bahrehmand et al., 2015):

$$\mathrm{Ex_{in}} = \left(1 + \frac{1}{3}\left(\frac{\mathrm{T_a}}{\mathrm{T_s}}\right)^4 - \frac{4\mathrm{T_a}}{3\mathrm{T_s}}\right)\mathrm{IA_c}\,, \qquad \text{(eq. 5)}$$

where,

η_{ii} (%) is the exergy efficiency of the collector

Ex_u(W) is the actual exergy delivered to the air

Ex_{in}(W) is the input exergy of the sun radiation

R (287 J.kg^{-1}.K^{-1}) is universal gas constant

ρ_i and ρ_o (kg.m-^{3}) are the air density

Ta (K) is the temperature of the ambient

Ts (K) is the temperature of the sun, 5600 K is assumed.

3. Results and Discussion

In this study, three different solar dryer arrangements were investigated experimentally. The energy and exergy efficiency of three different configurations were calculated directly from the data of each study case. The experimental results are presented in the form of graphs describing solar insolation, temperature rise through the collector, airflow velocity, energy efficiency and exergy efficiency as a function of time of day.

3.1. Airflow velocity and dry air temperature

The variation of airflow velocity at the collector inlet, dry air temperature at the chimney outlet (for Case-2) and at the drying chamber outlet (Case-1) as a function of time are shown in Fig. 2. During the experiments, the drying air temperature for Case-2 ranged from 29 to 51°C, and drying air temperature for Case-1 ranged from 46 to 57°C. The trend of temperature variations was similar for both cases. The variation in air temperature is mainly due to the occurrence of incident radiation on the dryer surface.

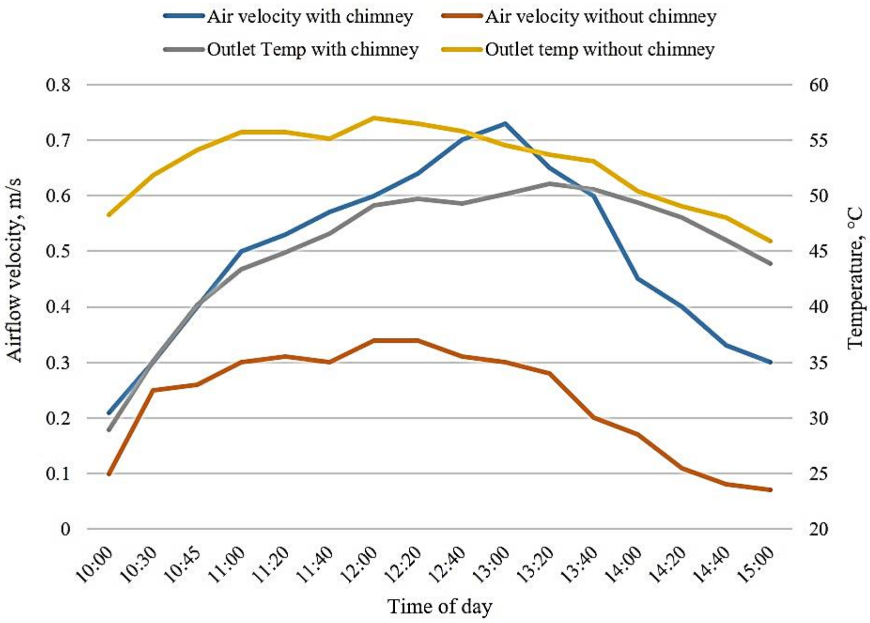
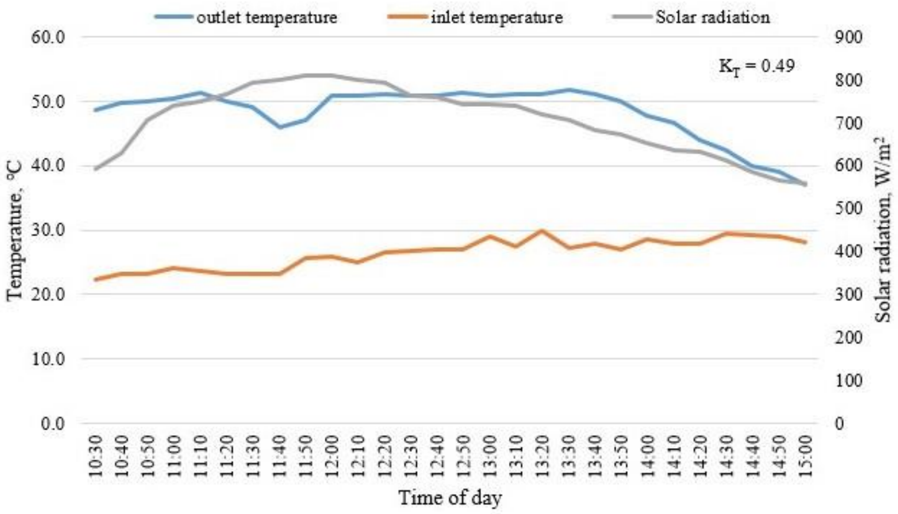


Fig. 2: Comparison of airflow and outlet temperature of a solar dryer with and without a chimney

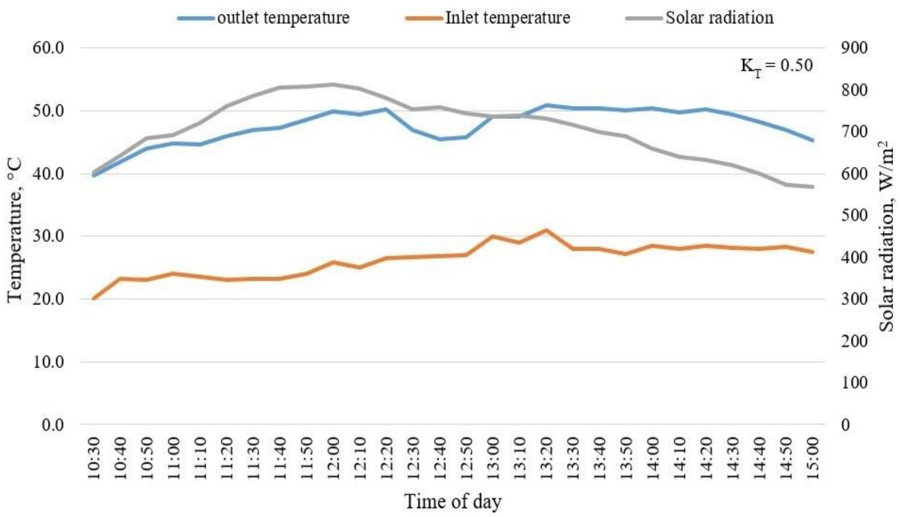
The velocity of the flowing air was measured at the collector inlet. Fig.2 shows the recorded value of airflow velocity as a function of time. The airflow velocity for Case-1 was about 0.3 m. s^{-1} while Case-2 obtained 0.7 m. s^{-1}. This increased airflow velocity showed that the passive solar dryer with a chimney (Case-2) was able to provide 60% more airflow than the one without a chimney (Case-1) under similar climatic conditions. The result can be explained by the fact that the airflow increases with the presence of the chimney. Chen and Qu (2014) made a similar observation. The airflow rate is mainly affected by the chimney height and the temperature difference between the average air temperature in the chimney and the ambient temperature. Fig. 2 also shows almost the same pattern in air temperature and velocity across dryer systems.

3.2 Temperature rise and solar radiation intensity at solar air collector

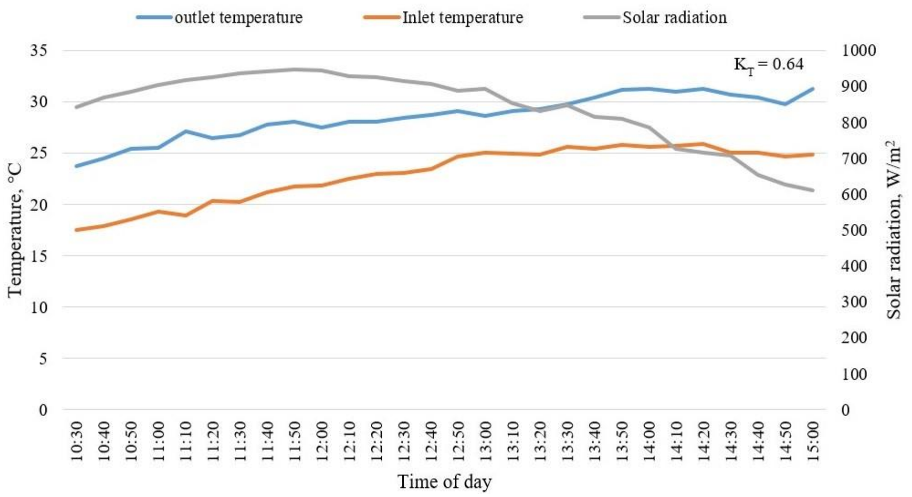
Fig. 3 (a-c) shows the variation of flowing air temperature at the inlet and outlet of the solar air heater and the solar radiation intensity measured during the experimental days. The values of solar radiation change in the range of 560 W m^{-2} and 950 W m^{-2} and reach the maximum at noon time. The inlet and outlet temperatures varied almost linearly with the incident solar radiation. Case-1 had a higher temperature rise than Case-3 and no significant difference with Case-2. As known, at lower air flow rate the air have more time to get hot inside the collector. It can also be seen that the average clearness index for Case-1, Case-2, and Case-3 are 0.49, 0.50, and 0.64 respectively. The clearness index is defined as the ratio of daily radiation to extraterrestrial radiation for the day (Duffie and Beckman, 2013). It indicates the clearer days (higher clearness indexes correspond to clearer days). The variation of temperature rises for Case-1, Case-2, and Case-3 are 9 to 23 °C, 7 to 18 °C, and 4 to 8 °C, respectively.



(a)



(b)

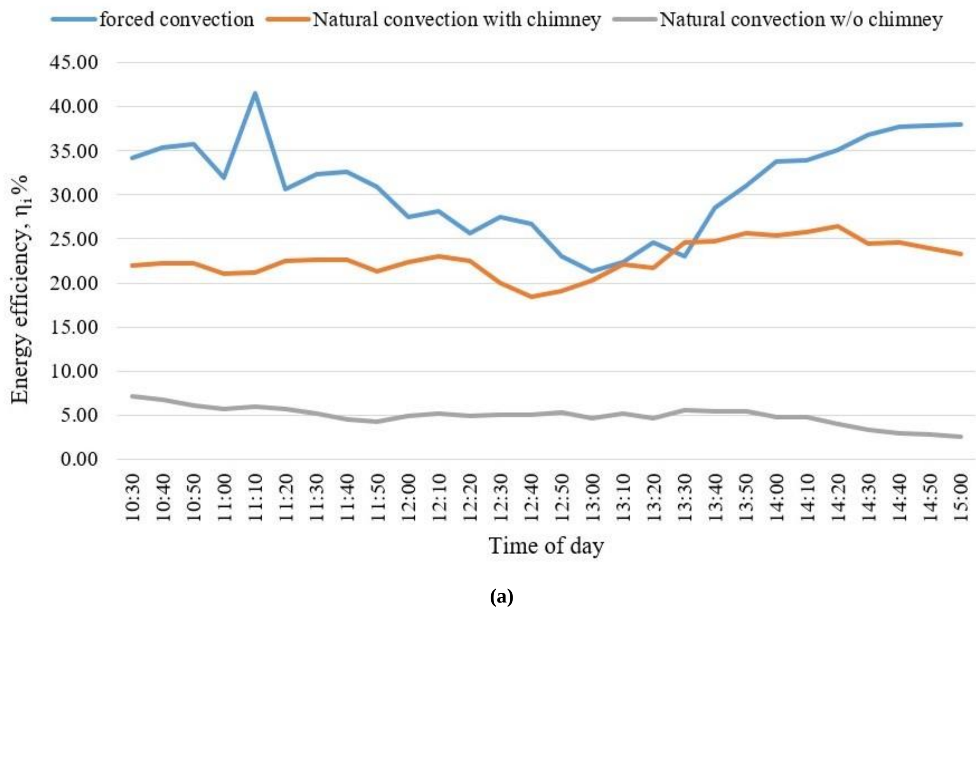


(c)

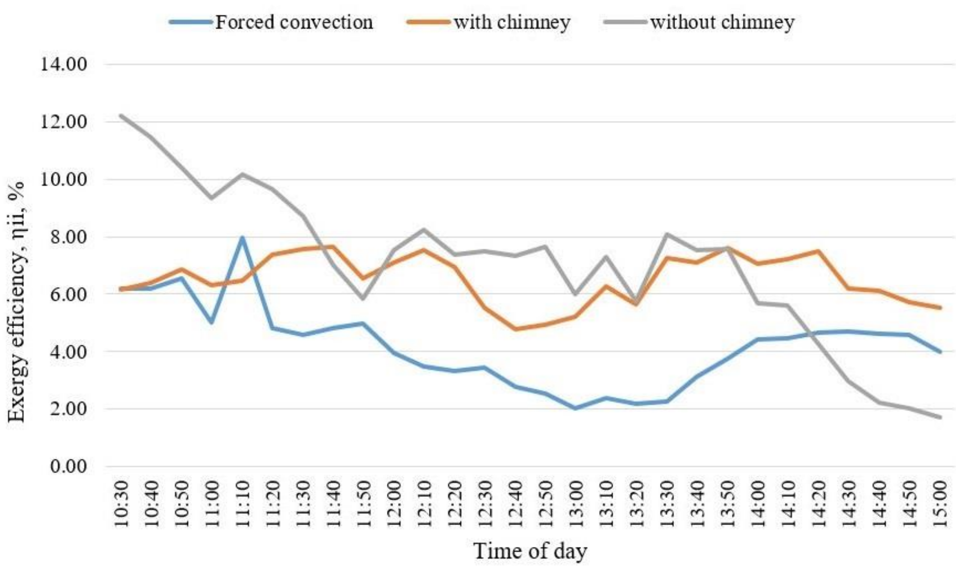
Fig. 3: Collector inlet and outlet temperatures and solar radiation: (a) Case 1; (b) Case 2; and (c) Case 3

3.3 Energy and exergy efficiencies of the collector

A plot of computed (using Eq. 1 and Eq.2) hourly energy and exergy efficiency curve of the collector for the three Cases (1-3) is shown in Fig. 4. Fig. 4(a) presents the energy efficiency of the collector. The efficiency varies between 3% and 7% for Case-1, between 20% and 26% for Case-2, and between 21% and 42% for Case-3. The highest energy efficiency was found for Case-3, whereas the lowest values were obtained for the dryer without a chimney (Case-1). This can be explained that airflow rate is very high in active solar dryer. The range of variation of the resulting values is due to variations of climatic conditions. The energy efficiency for Case-3 is higher, around 83.6% and 26% by comparing Case-1 and Case-2, respectively. The result show that a negative relationship between energy efficiency and temperature rise was observed. The trends of the daily exergy efficiency in all the cases were similar.



(a)



(b)

Fig. 4: The instantaneous energy and exergy efficiencies

The exergy efficiency on the collector, based on the three configurations, against the time of day is presented in Fig. 4(b). Solar dryer without chimney (Case-1) was obtained the highest exergy efficiency in comparison with active solar dryer due to low airflow rate occurred in this dryer. The values of exergy efficiency computed using Eq. (2) varies from 2 % to 12% in Case-1, from 5% to 8% in Case-2, and from 2% to 8% in Case-3. The variation of the efficiency value of chimney solar dryer and active solar dryer was similar. The exergy efficiency order of the three configurations was determined as dryer without a chimney, dryer with a chimney, and active solar dryer. It was observed that by lowering the airflow rate the exergy efficiency increased linearly. Table-2 presents the summary results of average daily energy and exergy gain together with energy and exergy efficiency. The highest total energy gain was obtained by the active solar dryer and followed by a chimney dryer. When compared as a percentage of the daily exergy gain, it was clearly seen that Case-2 had a higher percentage of exergy gain than Case-3. However, energy efficiency of Case-2 had a lower value than that of Case-3. As known, the air flow rate is the most significant parameter in evaluating a solar air collector’s thermal efficiency.

Tab. 2: Average daily energy and exergy efficiency

Type	Energy gain (kJ)	Exergy gain (kJ)	Energy efficiency %	Exergy efficiency %
Case-1	358.2	479	5.01	7.16
Case-2	1628.2	438.64	22.62	6.56
Case-3	2615.21	332.33	30.52	4.17

4. Conclusions

Main conclusions derived from the results of the present study as follows:

- The highest energy efficiency of the collector was achieved by the active solar dryer, whereas the lowest values were obtained for passive solar dryer without a chimney.
- The performance of a passive solar dryer can be enhanced by the chimney.
- The energy efficiency depends significantly on the solar radiation and air flow rate.
- The values of energy efficiency varied from 3% to 26% for passive solar dryer and from 21% to 42% for active solar dryer.
- The exergy efficiency of the collector under passive solar dryer without a chimney was found high in

this study.

- Energy efficiency is not sufficient to evaluate the performance of the dryer system. Exergy efficiency is a reciprocal of energy efficiency.
- This study will be beneficial to the interested researcher in the performance improvement of the passive solar dyers.

5. Acknowledgments

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