ABSTRACT

Due to the rapid growth in global energy demand and the expected depletion of traditional fossil fuels, finding alternative energy sources has become a very important issue in today’s society. Solar energy, as a renewable energy source, is receiving significant attention from researchers due to its minimal environmental impact and greater sustainability.

Solar energy is widely utilized in various industries, particularly in the drying sector [1]. Currently, many studies concentrate on assessing and improving the efficiency of solar dryers for enhanced utilization in the field of drying technology [2].

Solar dryers generally consist of an air collector, a drying chamber, and a chimney. The performance of solar dryers is influenced by various factors, and many studies aim to improve the drying efficiency of solar dryers by analysing these influencing factors [3].

Gilago and Chandramohan [4] studied the performance of passive and active indirect solar dryers in drying pineapples. The results show that compared to PISD, AISD had an average thermal efficiency improvement of 16.52% and a drying efficiency improvement of 22.7%.

Hosseini et al. [5] studied the effects of three different vertical fins—rectangular, triangular, and elliptical—on the performance of solar air heaters. The results indicate that the thermal performance of the rectangular fin solar air heater is the best, with thermal efficiencies 12.5% and 5.5% higher than those of the elliptical and triangular fin heaters, respectively.

Getahun et al. [6] studied the behaviour of solar drying equipment in drying experiments. They used a model to simulate the experimental process and compared the experimental results to assess the accuracy of the model. Selecting an appropriate model to predict the behaviour of the drying equipment. Based on that work, it can be stated that the Computational Fluid Dynamics (CFD) modelling can better describe various characteristics of the solar drying equipment, including the entire drying process, selecting the optimal drying conditions and techniques to maximize the efficiency of the drying equipment, producing high quality products that meet the standards.

Keywords: Air passes structures, Drying chamber, Solar air collector, Solar drying system.
The recent study presents the experimental results of an indirect solar dryer and analysed the influence of single and double pass solar air collectors on the drying performance.

2. Materials and Methods

2.1. Location of Solar Dryer System

The solar drying experiments were conducted in the Solar Energy Laboratory of the Hungarian University of Agriculture and Life Sciences, Gödöllő, Hungary, as shown in Fig. 1.

Solar collectors harness solar radiation and, besides any other applications, are utilized for drying purposes nowadays. In order to maximize the efficiency of the collector, based on the actual positioning in the laboratory, the solar dryer was positioned at specific angles and orientations.

2.2. Solar Dryer System

The installation of the experimental system is shown in Fig. 2. It is fixed on a metal frame at a designated location, with the main components connected through insulated air ducts. The solar modules are connected to the power supply, which is then connected to the blower. The outlet of the drying chamber is connected to a short chimney. Inside the drying chamber, there are five trays of the same size.

When the flat-plate solar collector operates, ambient air enters from the air inlet, undergoes heat exchange inside the collector, increases in temperature, and flows out from the upper air outlet. The overall structure of the flat-plate solar collector consists of a glass cover plate (1), an absorber surface (2), side box walls (3), an insulation layer (4), and a back-box wall (5) as shown in Fig. 3.

The drying chamber is an essential component of the solar drying system, its function is to place the items to be dried, remove the moisture from the items through heat exchange, reduce humidity, and achieve the purpose of drying. The experiment used polystyrene blocks with a thickness of 5 cm and a thermal conductivity of 0.035 W/mK to construct the drying chamber. The drying chamber consists of five plastic mesh tray spaced 10 cm apart. Each tray measures 38 cm in length and 40 cm in width. The chamber is connected to a solar air collector by a short duct, allowing air to enter the chamber from the collector's outlet and exit through the top ventilation opening of the drying chamber. The purpose of setting the inclination angle above the drying chamber is to ensure air circulation speed and enhance drying efficiency. The drying chamber design is shown in Fig. 4.

The function of a chimney is to accelerate the circulation of air, increase air flow, and enhance the effect of natural
Convection. The chimney effect can be used to describe the phenomenon where differences in air density drive circulation and create pressure difference in the chamber:

$$\Delta P_{\text{stack}} = gH \Delta \rho$$ (1)

where $\Delta \rho$ is the air density difference ($\text{kg/m}^3$), $P_{\text{stack}}$ represents the pressure difference caused by the stack effect (Pa), $g$ is the acceleration due to gravity ($\text{m/s}^2$), $H$ is height of the chimney (m).

When the dehydration system is operating, a pressure difference is generated, leading to air flow, with the specific formula as follows:

$$\Delta P = \rho g H \beta (T_{\text{ch}} - T_a)$$ (2)

where $\Delta \rho$ represents the pressure difference, $\beta$ is the coefficient of thermal expansion for air ($1/\degree \text{C}$), $T_{\text{ch}}$ represents the temperature of the air inside the chimney ($\degree \text{C}$), $T_a$ is ambient air temperature ($\degree \text{C}$).

Within the temperature range of 25–90 degrees, the relationship between air density and temperature is as follows:

$$\rho = 1.11363 - 0.00308 T$$ (3)

$$\Delta P_b = 0.00308 g H (T_{\text{ch}} - T_a)$$ (4)

$$\Delta P_b = f \rho \nu^2 H / 2D$$ (5)

The chimney structure has circular cross-section with a length of 1 m and a diameter of 0.1 m, constructed of plastic material.

### Table I: Thermometers Instruments Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>$-200$ to $1372 \degree \text{C}$</td>
</tr>
<tr>
<td>Power</td>
<td>9 V</td>
</tr>
<tr>
<td>Accuracy</td>
<td>$&gt;100 \degree \text{C} \pm 1 \degree \text{C}$</td>
</tr>
<tr>
<td>Size</td>
<td>$20 \text{ cm} \times 8.5 \text{ cm} \times 4 \text{ cm}$</td>
</tr>
</tbody>
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### 2.3. Equipment of Measurements

In the experiment, measuring experimental values using a thermocouple and a thermometer (Table 1), a hygrometer, a pyranometer, an anemometer, and a weighing scale.

Thermocouples are a type of temperature sensor with the characteristics of accurate and reliable temperature measurement, and a wide temperature measurement range. During the drying experiment, thermocouples are used to monitor and record the temperatures at different points for ease of analysis and future use.

The relative humidity gauge for experiments measures within the range of 10% to 99%, with a humidity accuracy of 4%. The sensor wire is 1.5 m long, and the probe is 0.06 m long. The relative humidity meter is shown in Fig. 5.

This experiment uses the MS6252A digital anemometer powered by a 9 V battery. The MS6252A accurately measures wind speed, airflow rate, and temperature to provide accurate environmental data for experiments. The anemometer is shown in Fig. 6.

The solar radiation is an important parameter affecting the experiment. During the experiment, a digital solar power meter was used to test and record solar radiation at different times. Table II lists the standards for instruments.

Before and after the drying process, we used a basic digital kilogram scale to weigh the dried products. The maximum capacity of the scale is 5 kg.
3. Result and Discussions

The experiments in this paper investigate the performance of the solar dryer by analysing the recorded experimental data along with measuring and recording the temperature and airflow rate. The calculation of the useful heat energy $Q_u$ is based on the temperature change ($T_o - T_i$) and airflow at the inlet and outlet of the collector:

$$Q_u = \dot{m} c_p (T_o - T_i)$$

where $c_p$ is the specific heat of the air (J/(kg °C)), $m$ is air mass flow rate (kg/s), $T_o$ is outlet temperature of air (°C), $T_i$ is inlet temperature of air (°C).

A digital anemometer was used in the experiment to measure the velocity. $A_{duct}$ is the area of air flow duct. The air mass flow rate can be calculated from the density and velocity:

$$\dot{m} = \rho v A_{duct}$$

where $v$ denotes air velocity.

The instantaneous thermal efficiency of a solar collector is a frequently used parameter for evaluating the performance of the collector. The specific calculation formula is as follows:

$$\eta = \frac{Q_u}{G A_C}$$

where $A_C$ is total amount of radiation collector surface, $G$ is solar radiation.

The experiments were conducted to compare the effects of single and dual return collector inlets, outlets, ambient temperature, solar radiation intensity, useful heat gain, effectiveness, and temperature stratification on solar dryers. The performance differences between single and dual return collectors are investigated by analysing relevant experimental data.

Fig. 7 illustrates the working principles of single-channel and double-channel collectors, showcasing two different airflow modes. The dual-channel has upper and lower channels, which can accelerate the airflow to some more extent.

Fig. 8 records the temperature changes of single pass and double pass collectors. It can be clearly seen during the experimental process that the output air temperature fluctuates indirectly with the ambient temperature. For a single pass air solar collector, the trend of the outlet temperature curve rises and then falls with time, reaching its peak around 14:00 in the afternoon. The overall trend is roughly similar to the inlet temperature and ambient curves. For double-pass solar collectors, the trend of outlet temperature distribution is similar to the trend of secondary inlet temperature distribution. The temperature
distribution at the first inlet is very close to the ambient temperature distribution. The outlet temperature curve reaches a maximum of 39 °C at 13:00 in the afternoon. The maximum temperature difference between the top and bottom channels is 9.5 °C.

Fig. 9 shows the variation of the curves of solar radiation intensity irradiance and total available heat for two different collectors. The solar radiation profile of the single-pass solar collector increases with time and reaches a maximum value of 950 W/m² at 12:00 p.m. The total available heat of the single-pass solar collector increases over time, with a daily total of 3260 kJ available heat. The solar radiation curve of the flat-plate double-pass collector is roughly similar to that of the single-pass solar collector. The available heat of the double-pass collector fluctuates minimally between 10:00–13:00.

Fig. 10 depicts the instantaneous thermal efficiency in two different collector drying processes. For a single-pass solar collector, the instantaneous efficiency reaches a maximum value of 56% at 14:40. The instantaneous efficiency of the double-pass collector is around 60% at its peak. The instantaneous efficiency of the double-pass collector is higher, increasing as the collector temperature rises.

Fig. 11 depicts the average temperature change in the drying chambers of two different collectors. The average temperature difference between the single-pass and double-pass drying chambers is small, and the temperature variations are not significant, and the curves converge. The ambient temperature profile increases with time.

Fig. 12 shows the average relative humidity in the solar collector drying chamber over time. The ambient humidity was about 60% at the beginning and about 33% at the end of the experiment. The average humidity in the ambient, single-pass, and double-pass collector drying chambers was 31%, 26.5%, and 24%, respectively. The average relative humidity was higher for the single-channel collector.

Fig. 13 depicts the experimental performance curves of two different collectors. By calculating the equation from the experimental data, the efficiency of the solar collector is linearly related to the temperature difference, and the relevant linear equations are as follows:

\[ \eta = a \frac{T_{\text{av},\text{s}} - T_{\text{a}}}{I} + b \]
Fig. 10. Collector instantaneous efficiency.

Fig. 11. Average temperature of drying chamber.

Fig. 12. Average relative humidity in drying chambers.
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where $a$ represents the gradient of system efficiency $T_{ax}$ represents the average temperature of the system (°C), $T_a$ denotes the ambient temperature (°C), $I$ is the solar irradiance (W/m²), $b$ is a coefficient that represents the baseline efficiency of the system.

As can be seen in Fig. 13, in the case of the single-pass collector, the equation has larger parameter values, indicating a greater variation in thermal transient efficiency versus temperature difference ($\Delta T/I$) over solar radiation. In the case of the two-pass collector, the equation indicates a smaller slope and a flatter curve. The performance of the dual-pass collector is more stable.

4. Conclusion

This study investigated the performance of single-pass and double-pass dryers. The results indicate that the air temperature in the drying chamber is influenced by the available heat. The maximum solar radiation value reaches 950 W/m² at 12:00. The maximum temperature difference between the top and bottom channels of the double-pass collector is 9.5 °C. The average humidity in the drying chamber for single-pass and double-pass collectors is 26.5% and 24%, respectively, with instantaneous peak efficiencies of approximately 56% and 60%, respectively. Compared to the single-pass collector, the double-pass collector shows better performance in drying.

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CONFlict OF INTEREST

The authors declare that we do not have any conflict of interest.