



Experimental Investigation of the Thermal Performance of Porous-Media-Integrated Solar Air Collectors Under Variable Airflow Velocities and Real Climatic Conditions

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ABSTRACT

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The thermal performance of solar air collectors integrated with the porous media was experimentally investigated under variable airflow velocities and realistic climatic conditions. Two geometrically identical solar air collectors were designed, fabricated, and experimentally evaluated, with each collector packed with a different porous medium, namely glass spheres and metallic fibres, to enhance convective heat transfer and thermal energy storage characteristics. The experimental campaign was conducted on the rooftop of Hawija Technical Institute, Iraq, over three consecutive months (August–October), during which inlet air velocities of 1.0, 2.0, and 3.5 m s⁻¹ were imposed under naturally varying solar irradiation conditions. The thermal behaviour of the collectors was assessed through the analysis of key performance indicators, including outlet air temperature rise, useful thermal energy gain, and instantaneous thermal efficiency. It was observed that the integration of porous media significantly improved thermal performance by increasing the effective heat transfer surface area, promoting flow mixing, and enhancing energy retention within the absorber region. Furthermore, a strong dependence of thermal performance on airflow velocity was identified. As the air velocity increased, improved heat extraction from the absorber surface was achieved, resulting in higher useful energy output and enhanced collector efficiency. Under the highest tested airflow velocity of 3.5 m s⁻¹, the useful thermal energy gain reached approximately 200 W, whereas values of approximately 190 W were recorded under lower airflow conditions. The maximum thermal efficiency was found to reach approximately 58%, while efficiencies under lower operating conditions remained within the range of 52–57%, depending on airflow rate and environmental conditions. Comparative analysis further indicated that the collector packed with metallic fibres exhibited superior thermal responsiveness, whereas the glass-sphere configuration demonstrated improved thermal storage stability. These findings demonstrate that the combined optimisation of porous medium characteristics and airflow velocity can substantially improve the thermal effectiveness of solar air collectors, thereby supporting their applications in sustainable heating and solar energy utilisation systems.

1. INTRODUCTION

The world is expected to face several significant challenges in the coming decades, including the depletion of fossil fuel reserves, as recent data reveal that the proven oil reserves, for example, may be depleted within the next 60 years, which means that many countries are now shifting to renewable energy sources of all kinds instead of traditional energy sources [1]. Moreover, the environmental pollution caused by the use of fossil fuels has significantly contributed to global warming and climate change. Renewable energy sources can be broadly classified into several types, including solar, wind, geothermal, and hydropower energy. Solar energy has attracted considerable research attention as it is the most suitable and feasible option to replace fossil energy [2].

Solar energy is a clean, renewable, and sustainable energy source that contributes significantly to reducing environmental pollution and meeting the growing global energy demand [3]. Among its most prominent uses are: generating electricity using photovoltaic panels, heating water via solar heaters, and powering heating and cooling systems in buildings [4]. Solar energy is also employed in desalination and agricultural applications, such as pumping water for irrigation, thereby making it a sustainable alternative across a wide range of areas. There are three major types of solar energy systems. The first type consists of photovoltaic systems, in which solar radiation is directly converted into electricity through photovoltaic cells. These systems are widely deployed in domestic applications, commercial facilities, and large utility-scale industrial applications [5]. Solar thermal systems,

including solar water heating and space heating applications, use solar energy to heat liquids or gases. Concentrated solar power (CSP) systems employ mirrors or lenses to focus solar radiation onto a working fluid, and the generated thermal energy is then used to power steam turbines in solar power plants. Other solar systems are hybrid systems that combine solar energy with other energy production technologies (such as wind or battery storage systems), thereby improving energy efficiency and facilitating continuity of energy supply in varied applications [6]. Solar air heaters are considered an effective solution for building heating, as they depend on absorption of sunlight and the absorption of sunlight and its conversion into heat, which is then transferred to the airflow for heating homes, warehouses, farmhouses, and factories [7]. Solar air heaters can be classified as active or passive. To drive air through a heater and into a building, active systems require fans and/or pumps. Passive systems use convection to move air without needing any energy [8, 9]. The main components of a flat solar collector include a transparent glass cover placed above the absorber plate, which is enclosed and insulated by the outer shell [10]. The materials used to make the solar collector must be able to withstand high temperatures, so the absorber board is usually made of metals with high thermal conductivity [11]. Copper is considered the best choice due to its excellent thermal performance, despite its high cost, and aluminum or stainless steel are often used as lower-cost alternatives [12]. The collector parts are mounted inside a structure, which is commonly constructed of stainless steel or wood, and are insulated on the sides and rear to prevent heat losses. However, some losses occur due to the temperature difference between the absorber plate and the ambient air [13]. The glass cover that is placed on the flat panel solar collector faces the sun, allowing the majority of the solar radiation to pass through to the absorber plate. However, it is vital to remember that the glass absorbs and reflects some of the incident sunlight, with only a portion going through to the absorber plate [14]. Flat solar collectors usually allow about 80-90% of the solar radiation to pass through, while the other part is absorbed or reflected by the glass. In addition, the glass cover contributes to the reduction of heat losses due to convection and radiation, and also protects the absorber plate from external factors such as rain or dust [15]. Porous media improve the thermal efficiency of solar collectors by increasing the effective heat transfer surface area and modifying the airflow pattern, which enhances airflow disturbance and promotes better air mixing [16].

To control the temperature of solar panels efficiently, air is commonly used as a heat transfer medium [5], as it is considered the best choice for the purposes of circulating and preheating [17].

Zhang et al. [18] conducted a study to assess the effect of coolant flow rates and liquid inlet temperature on the efficiency of the solar collector. The flow rates were adjusted at different values, and the researchers noted that increasing the flow rate of the liquid helps to transfer heat faster from the absorber plate to the liquid, which reduces the overheating of the plate and limits heat loss. The results showed that the thermal efficiency of the collector reached 65% at a flow rate of 0.03 kg/s, with a noticeable improvement in the temperature stability of the fluid inside and outside the collector. The study indicated that choosing an appropriate flow rate helps to achieve a balance between heat transfer and energy efficiency. Tekkalmaz et al. [19] conducted an experimental study of a flat solar collector equipped with a double glass cover instead

of the traditional single glass cover. The double glass cover reduces the heat loss caused by convection and radiation, as the air layer between the two covers traps heat. The efficiency of the collector was measured under similar operating conditions to a conventional collector, and it was found that a double glass cover increases thermal efficiency by up to 12% compared to a single cover. This design also helped to raise the temperature of the outlet liquid, which increases the efficiency of using solar energy in various applications. Cruz et al. [20] conducted a study on the effect of adjusting the angle of inclination of the solar collector depending on the position of the sun during different seasons of the year. The collector is usually installed at a fixed angle, but the researchers periodically changed the angle of inclination to correspond to the height of the sun in the sky. The results showed that periodically adjusting the angle leads to an increase in the amount of solar radiation reaching the collector, thereby improving thermal absorption. This resulted in an increase in thermal efficiency of up to 18% compared to the fixed-angle configuration, especially during spring and autumn, when the position of the sun changes rapidly. Patel [21] compared the effect of different types of heat transfer fluids inside flat solar collectors, such as purified water, water mixed with ethylene glycol, and thermal oils. It was found that liquids with higher thermal conductivity improve heat transfer from the absorber plate to the distribution system faster and more effectively. For example, the use of a mixture of ethylene glycol and water increased thermal efficiency by up to 20% compared to using only ordinary water, especially in cold weather conditions where glycol reduces the freezing of the liquid and improves performance.

El-Sebaei et al. [22] conducted an experiment on a flat solar collector with the addition of thermal insulation on the back side of the absorber plate. The goal of insulation is to reduce the heat loss caused by heat transfer from the rear side to the surrounding environment, which is a major reason for the low efficiency of the collector. The results showed that thermal insulation contributed significantly to reducing the back heat losses, which led to increasing the daily thermal efficiency of the collector by up to 15%, especially on days with high solar radiation and light winds. The study confirmed that improving insulation is one of the important factors in improving the performance of solar collectors. Solar air heaters have attracted increasing attention due to their simple design, low maintenance requirements, and suitability for space heating, drying, and ventilation applications. Unlike liquid-based collectors, air-based systems are free from leakage, corrosion, and freezing issues, making them particularly suitable for arid and semi-arid regions. Several studies have demonstrated that the thermal performance of solar air heaters can be significantly enhanced by incorporating porous media within the airflow channel. Porous materials increase the effective heat transfer area and promote turbulence, resulting in improved convective heat transfer between the absorber plate and the flowing air [23]. Various porous media configurations have been investigated to enhance the thermal efficiency of solar air collectors, including packed beds, wire meshes, metallic foams, gravel, and fibrous materials. Glass spheres have been reported to provide favorable thermal storage characteristics due to their high heat capacity and ability to retain thermal energy, while metallic fibers are known for their high thermal conductivity, enabling rapid heat absorption and transfer. The selection of porous media type plays a crucial role in determining the balance between thermal efficiency,

pressure drop, and airflow behavior. However, limited experimental studies have addressed the combined influence of porous media characteristics and air velocity under real outdoor operating conditions, which represents a key research gap addressed in the present study.

This study aims to experimentally investigate the combined influence of air velocity and porous media characteristics on the thermal performance of a solar air collector under real climatic conditions. The analysis focuses on temperature rise, useful thermal energy, and thermal efficiency to identify optimal operating conditions. Given that the air velocity directly affects the ability of the solar collector to transfer heat and increase the efficiency of the system, choosing the optimal speed is an essential step to improve the overall performance of solar collectors. This study will provide a scientific basis to improve the design and operation of solar energy systems in accordance with practical and environmental requirements. Therefore, the experimental methodology was designed to evaluate the interactive role of airflow rate and porous media in enhancing heat transfer and thermal efficiency.

2. METHODOLOGY

Solar air collectors are one of the critical sustainable energy solutions that contribute to economic development by providing a low-cost and effective means of producing thermal energy from a free and non-polluting resource, namely sunlight, rather than relying on fossil fuels, thereby increasing energy costs, particularly in agricultural and industrial sectors that frequently use heated or dried products. Local manufacturing, installation, and maintenance of these systems create jobs and support rural and remote communities by providing a simple and reliable energy source that enhances energy security, increases productivity, and reduces the environmental costs associated with energy production, making it a powerful sustainable development tool for achieving equitable and sustainable economic growth. This study is aimed at analyzing the effect of different air speeds on the performance of the solar collector and selecting the optimal speed that contributes to improving the efficiency of heat absorption and energy conversion. The research will be divided into the following parts: practical part in Section 3, mathematical equations in Section 4, results in Section 5, and conclusions in Section 6.

3. EXPERIMENTAL METHODOLOGY

To investigate the influence of different air speeds on the performance of solar collectors and determine the optimal speed for improving efficiency, two identical practical models were constructed. These models were set at a specific angle and placed under local weather conditions to evaluate their thermal performance. The solar collectors were installed on the roof of the Renewable Energy Research Unit at the Hawija Technical Institute, which is located in northern Iraq at the coordinates (35.19° N, 43.46° E). The building has a height of 8 meters, and the setup aimed to assess how variations in air velocity impact the efficiency of the solar collectors. The adopted model of the solar collector includes system description, absorber plate, and inlet and outlet fans.

3.1 Solar collector

The device shown in Figure 1 has a rectangular box-like design as it sits on a rectangular base with wheels to allow for the directional angle to be adjusted. The structure consists of the following items.

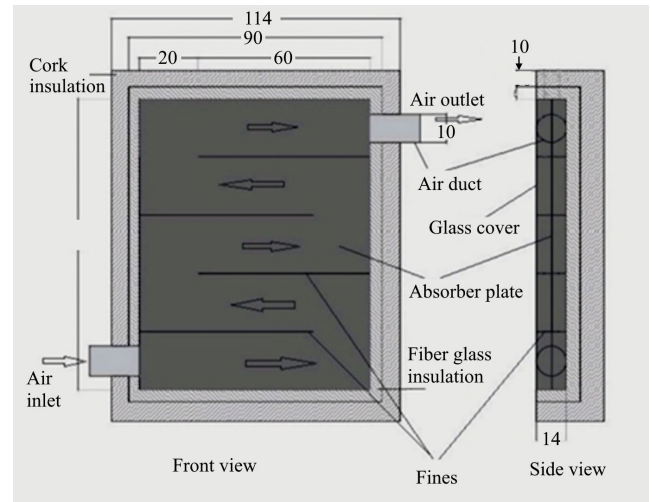


Figure 1. Dimensions (cm) of the solar collector

3.1.1 Steel frame

The steel structure consisted of 0.9 mm thick steel sheets, in the form of an open box, with dimensions of 100 cm × 80 cm × 10.2 cm in length, width, and height, respectively. There are also side openings in the structure.

3.1.2 Device base

The base of the device is made of cast iron and has the following dimensions: length (120 cm), width (100 cm), and height (5 cm), as it is cast in a rectangular shape. The base has four plastic wheels so that it can move and change direction.

3.1.3 Thermal insulation

To reduce heat loss, the device is coated with two layers of thermal insulation. The first layer is a 5 cm thick layer of glass wool, which was chosen for its effectiveness as a thermal insulation material. A second layer of cork insulation measuring 10 cm thick was added to the first layer to improve insulation and prevent lateral or bottom heat losses from the device.

3.1.4 The glass cover

To provide proper thermal insulation, the device was covered with a double-glazed glass cover, which consisted of two layers separated by an air gap. Each layer of glass is 4 mm thick, with a 9 mm air space between them. The glass has a light transmission value ($\tau = 0.92$) and an emissivity value ($\epsilon = 0.88$).

3.1.5 Wooden casing

The item was sheathed on the outside with the outer wooden layer to improve its design and appearance. An iron plate measuring 2 mm thick, 100 cm long, and 80 cm wide was employed, with four fins on each side to increase the surface area of absorption and improve mixing. Each fin is 60 cm long, 5 cm wide, and 0.9 mm thick, and it was arranged in a non-uniform pattern to allow air to move between them. To keep the board from bowing under the weight of the porous

medium, a frame was built around it, leaving two sides free for air access. The board and fins were painted with matte black coating, which is heat-resistant and can withstand temperatures above 600 °C. Two small entry and exit fans with a power of 26 W were installed to operate the device under forced convection conditions and control air speed for entry and exit, as shown in Figure 2.



Figure 2. Wooden casing for the device

3.2 Experimental procedures

Experimental tests have been conducted in August at (1 m/s), September at (2 m/s), and October at (3.5 m/s) to study the effect of different air speeds on the performance of the solar collector. These months were chosen due to the mild weather conditions and the high availability of solar radiation in the region. The experiments were carried out on days with clear skies and light winds to ensure the consistency of environmental conditions, which contributes to minimizing the impact of environmental changes on the results of the experiments. The emphasis was placed on minimizing the influence of extreme seasonal factors to ensure accurate results reflecting the performance of the solar collector in conditions close to real-world conditions.

3.3 Apparatus and tools utilized in the experiment

To guarantee precise results and the lowest percentage of measurement error, the information presented here was gathered using high-precision, low-uncertainty measuring equipment. To ensure accurate data, the measurements were conducted at the location where the device was installed. The names and operating modes of the devices that were utilized are listed below. The solar system was placed in the same location, facing the sun, as the weather station, which was situated on the roof of a 6 m high building in Hawija city. The weather station, using the Vantage Pro2 system (Davis Instruments), is a device that measures solar radiation, atmospheric pressure, relative humidity, wind speed, and other relevant meteorological parameters.

An Applent (AT4516) multi-channel temperature monitoring device was utilized. Sixteen K-type thermocouples with an error tolerance of ± 1 °C were included with this multi-channel temperature measuring equipment. To guarantee reliable temperature readings, the device was calibrated before use. In order to guarantee precise readings for the models being examined, the multi-channel temperature measuring apparatus was additionally calibrated as follows: four channels were used to measure the absorber plate temperature; two channels were used to measure the inlet and outlet air temperatures; and four channels were used to obtain

temperature data from the porous media region. Air velocity was measured using a hot-wire anemometer (± 0.03 m/s). This instrument is specifically developed for measuring air velocity inside pipes and ducts. An extensible lever has been attached to the end of the instrument, which allows precise measurements of air velocity.

4. PERFORMANCE EVALUATION

Using the following formula to predict the absorbed solar energy by the collector [24]:

$$Q_u = \dot{m} c_p (T_{out} - T_{in}) \quad (1)$$

In this formula:

\dot{m} : mass flow rate of air;

c_p : specific density at constant pressure of air;

Q_u : the heat gain;

T_{in} : the entrance temperature of the air to the collector absorber;

T_{out} : The exit temperature of the air leaves the collector absorber.

in which [25]:

$$\dot{m} = \rho A_d V_{air} \quad (2)$$

where,

A_d : heater inlet cross-sectional area;

V_{air} : velocity of air;

ρ : air density, which can be found as follows [26]:

$$\rho = 1.1614 - 0.00353[(T_{out} + 273) - 300] \quad (3)$$

The specific heat can be determined using the following formula [24]:

$$c_p = [1.007 + 0.00004((T_{out} + 273) - 300)] \times 10^3 \quad (4)$$

The thermal efficiency of the solar collector is calculated as follows [27]:

$$\eta_{th} = \frac{Q_u}{I_{solar} \times A_{front}} \times 100\% \quad (5)$$

Assessment of Uncertainty

The results include a margin of error that is a function of the limitations of the equipment used in the study, with error rates for the devices used. The following equation was used to calculate the error rate of the equipment used in the study [28]:

$$\omega_R = \sqrt{\left(\frac{\partial \eta}{\partial x_1} \times \Omega_1\right)^2 + \left(\frac{\partial \eta}{\partial x_2} \times \Omega_2\right)^2 + \dots \dots \left(\frac{\partial \phi}{\partial x_n} \times \Omega_n\right)^2} \quad (6)$$

5. RESULTS AND DISCUSSION

The practical study was carried out to evaluate the performance of the solar collector during three months (August, September, and October 2024), and the effect of different air speeds on the efficiency of the collector was

studied. Air velocities were set at different values: in August (1 m/s), in September (2 m/s), and in October (3.5 m/s). The first day of each month was chosen to conduct the study, as the weather conditions were ideal with no high winds and clear skies, in order to accurately assess the impact of different speeds on the performance of the solar collector.

5.1 Intensity of solar radiation

Figure 3 shows the intensity of solar radiation during the day from 9 AM to 4 PM for the months of August ($V = 1$ m/s), September ($V = 2$ m/s), and October ($V = 3.5$ m/s). At 9 am, the intensity of solar radiation is relatively low; in October, it registers about 140 W/m^2 , which is higher than in September (120 W/m^2) and August (90 W/m^2), which indicates a faster onset of radiation spikes in October. As time progresses, the intensity of radiation increases significantly in all months, peaking at 13:00, with October recording the highest value of about 485 W/m^2 , followed by September (460 W/m^2) and August (445 W/m^2), which indicates that October has the highest ability to receive solar radiation during the peak period. After that, the radiation intensity gradually begins to decrease during the afternoon, and the values become close at 16:00, with October recording about (150 W/m^2), followed by September (175 W/m^2) and August (145 W/m^2). From these results, it can be concluded that October is characterized by the highest intensity of solar radiation throughout the day, reflecting a possible impact on the efficiency of solar thermal systems that rely on radiation as the main source of energy.

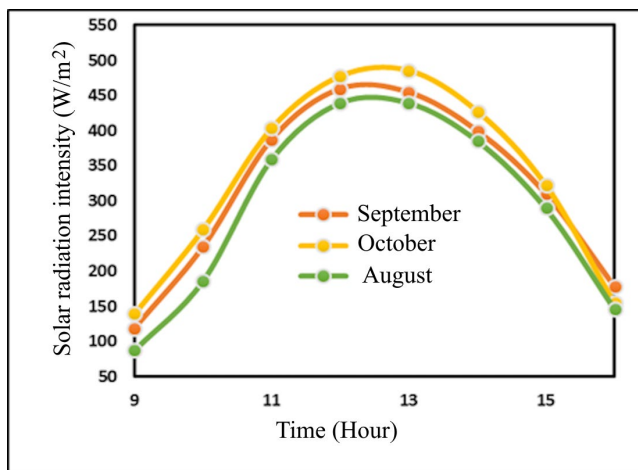


Figure 3. Solar radiation intensity

5.2 The air temperature difference

Figure 4 shows the temperature difference between the air outlet and inlet ($T_{out}-T_{in}$) during the day, from 9 AM to 4 PM, for the months of August ($V = 1$ m/s), September ($V = 2$ m/s), and October ($V = 3.5$ m/s), reflecting the performance of the thermal system in converting solar energy into useful heat. At 9:00 am, the three systems begin with relatively low thermal differentials, with August registering about ($1 \text{ }^\circ\text{C}$), slightly ahead of September ($0.8 \text{ }^\circ\text{C}$) and October ($0.5 \text{ }^\circ\text{C}$). This suggests that heating is still in its early stages, and solar radiation at this hour has not reached a level sufficient to cause significant thermal differences in all systems. As time progresses and the intensity of solar radiation increases, thermal differences begin to gradually increase in all months, peaking at 12:00 at noon. At the moment, the August regime

achieves the highest thermal difference of about $14 \text{ }^\circ\text{C}$, reflecting a high ability to absorb radiation and convert it into heat inside the air duct. In contrast, the September system records a good thermal difference of $8.2 \text{ }^\circ\text{C}$, while the October system records the lowest value among the three ($6.5 \text{ }^\circ\text{C}$), which may indicate the influence of different climate conditions, such as a decrease in ambient air temperature or a change in the angle of incidence of solar radiation. After the peak period, the thermal differences begin to gradually decrease during the afternoon hours. At 14:00, the performance decreases, but August still maintains its superiority by recording $12 \text{ }^\circ\text{C}$, while September and October record lower differences (about $6.5 \text{ }^\circ\text{C}$ and $6.2 \text{ }^\circ\text{C}$, respectively), which indicates that the system retains more heat in August. By 16:00 PM, the thermal differences in all systems converge, ranging from $1.5 \text{ }^\circ\text{C}$ to $2 \text{ }^\circ\text{C}$, which reflects the end of the effective period of gaining thermal energy from the sun. These results indicate that August is characterized by superior thermal performance due to the likelihood of more favorable radiation and climate conditions, and also highlight the importance of system design in improving the efficiency of heat absorption and storage. The difference between the three months reflects the decisive role of the climate, the material used, and the geometric structure of the solar system in determining its efficiency throughout the day.

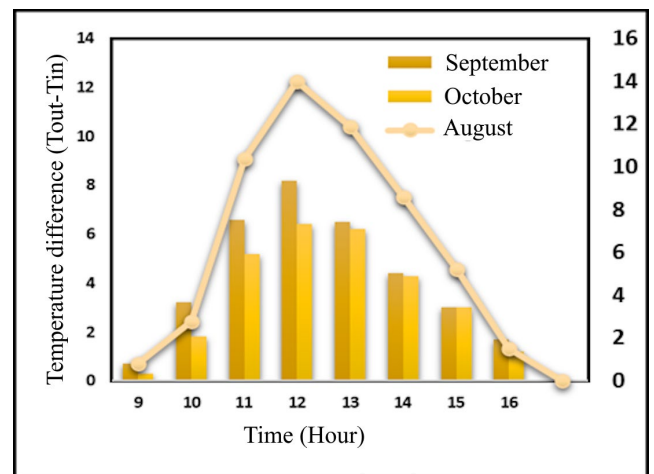


Figure 4. The difference in temperature ($T_{out}-T_{in}$) between the exit and the entrance

5.3 Average air inlet and outlet temperature

Figure 5 shows the average temperature (T_{mean}) during the day from 9:00 AM to 4:00 PM for the months of August ($V = 1$ m/s), September ($V = 2$ m/s), and October ($V = 3.5$ m/s), highlighting the thermal differences resulting from the thermal performance of the solar system during different months of the year. At 9:00 AM, October records the highest average temperature (about $14.5 \text{ }^\circ\text{C}$), followed by September ($10 \text{ }^\circ\text{C}$), then August ($8.5 \text{ }^\circ\text{C}$), indicating a differentiated heating onset reflecting the influence of changing climatic conditions between the months, as ambient temperatures in October may be higher in the morning compared to August. At 10:00 AM, the relative superiority of October continues to be recorded ($16 \text{ }^\circ\text{C}$), September comes in second ($15 \text{ }^\circ\text{C}$), while August remains relatively low ($10 \text{ }^\circ\text{C}$), which may be associated with a delayed response of the system in August or a decrease in solar radiation during the early morning hours. As we progress towards the middle of the day, namely at 12:00 PM, the values

converge significantly. Remarkably, the three systems record close temperatures ranging from 19 °C to 20 °C, reflecting a state of relative thermal stability as a result of solar radiation reaching its peak. At 13:00, the average temperature reaches its highest value during the day in October (22 °C), slightly surpassing August and September (both around 21 °C), which indicates a temporary advantage for the system's performance in this month during the peak period, possibly due to the composition of the material or the angle of incidence of solar rays. After that, the average temperatures begin to gradually decrease as the end of the day approaches. At 14:00, a clear decline appears in October (to 17.5 °C), while August and September maintain relatively stable performance (21 °C and 20.5 °C, respectively). This trend continues until 16:00 PM, as the values converge significantly between the three months, all recording an average temperature range of 17 °C to 18.5 °C. These results reflect the variability in the response of the thermal system to seasonal climatic conditions, since it is observed that the performance is influenced by factors such as ambient temperature, solar radiation intensity, and angle of incidence.

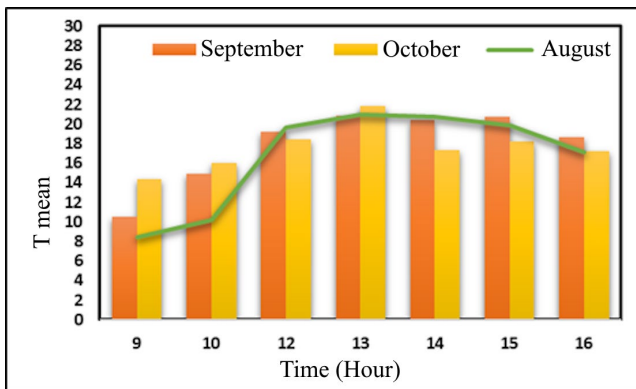


Figure 5. The average temperature between entry and exit

5.4 The useful thermal energy of the solar collector

Figure 6 shows the amount of useful energy extracted from the solar system during daylight hours from 9:00 AM to 4:00 PM for the months of August ($V = 1$ m/s), September ($V = 2$ m/s), and October ($V = 3.5$ m/s), highlighting the differences in thermal performance efficiency depending on seasonal climatic conditions. At 9:00 am, a generally low performance appears, with August registering the highest value (approximately 25 units), followed by September (about 15 units), and then October (about 10 units), which indicates a faster thermal response in August, possibly due to higher ambient temperatures or greater heat accumulation. At 10:00 am, the values noticeably converge between the three months (about 70–75 units), reflecting the beginning of the system's response to increased solar radiation during the post-sunrise period, with a slight preference for August. By 11:00, the differences become more pronounced; October is clearly ahead (about 165 units), followed by September (140 units), and then August (110 units). This increase in October may be due to a more optimal angle of incidence of sunlight in this month or improved absorption due to thermal characteristics adapted to autumn conditions. At 12:00, the performance peaks for all months, with October recording the highest value (more than 200 units), followed by September (180 units), and then August (150 units). Starting at 13:00, a gradual decrease begins. At 14:00, the decline continues, and October again

shows the highest value (about 120 units), followed by September (110 units) and August (less than 100 units). By 15:00, the values continue to decrease, and at 16:00, the values converge among the three months (35–40 units), reflecting low performance near sunset. August shows relatively lower performance during most of the day, which may indicate a negative impact of high temperatures or lower radiation intensity in the morning. The convergence of performance at sunrise and sunset suggests that system performance during these periods depends mainly on available solar radiation. Based on the experimental data, the maximum useful thermal power extracted from the solar air collector reached approximately 200 W at an air velocity of 3.5 m/s during peak solar radiation hours, while lower airflow conditions yielded values close to 190 W. Similarly, the highest thermal efficiency recorded was approximately 57%, whereas efficiencies around 52% were observed at lower air velocities.

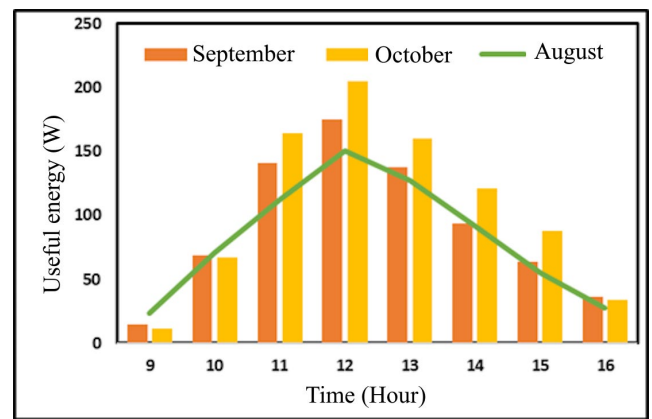


Figure 6. The useful thermal energy of a solar collector

5.5 Thermal efficiency of the solar collector

Figure 7 shows the thermal efficiency of the solar system during daylight hours from 9:00 AM to 4:00 PM for the months of August ($V = 1$ m/s), September ($V = 2$ m/s), and October ($V = 3.5$ m/s), explaining the differences in efficiency of converting solar radiation into thermal energy depending on seasonal climatic conditions. At 9:00 AM, October records the highest efficiency (about 21%), followed by September (15%), then August (less than 14%), which indicates an early and distinct thermal response in October as a result of higher atmospheric heat or better morning radiation characteristics, while low values in August reflect the weak thermal performance of the system during the early morning. At 10:00 am, the difference between the months widens, with efficiency increasing in October to about 40%, compared to 35% in September and 24% in August. At 11:00, October records a jump in efficiency to exceed 50%, while September remains at 45%, and August is lower (about 39%). This high performance reflects improved energy absorption and conversion in October, possibly due to a more favorable angle of solar incidence. By noon (12:00), the efficiency reaches its peak in October (approximately 58%), followed by September (47%), then August (45%). At 13:00, the efficiency begins to gradually decrease while maintaining the same order. At 14:00, the efficiency decreases further: October (42%), September (36%), and August (33%). At 15:00, a clear decline appears, with October registering about 36%, compared to 32% for September and 24% for August. Finally, at 16:00, the values converge at 26–27%, indicating a general decrease in

efficiency due to reduced solar radiation and lower incidence angles, as well as depletion of stored thermal energy.

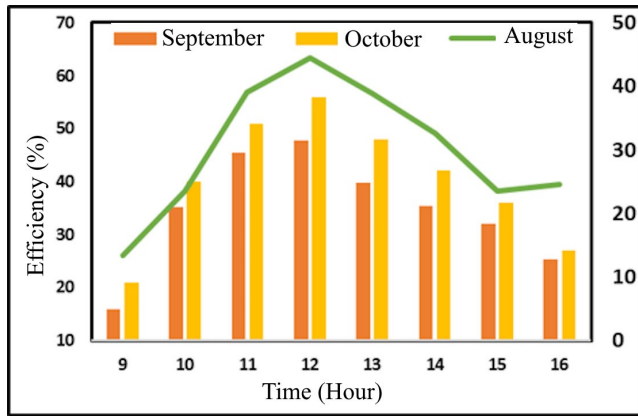


Figure 7. A comparison of the thermal efficiency of two different systems

5.6 Techno-economic implications

Besides thermal performance, the economic aspect of solar air collectors is also important for assessing the feasibility of such systems. Although both glass and mineral fiber balls exhibit good thermal performance, glass balls have economic advantages due to their low cost and easy availability. Metal fibers are more expensive but can be justified in applications with high performance requirements that demand a rapid response during peak solar radiation periods. This illustrates the trade-off between thermal performance and economic feasibility that exists when selecting the appropriate porous media for solar collectors. In the future, it is necessary to consider this balance when implementing large-scale solar systems, so that the optimal operating conditions are determined to ensure high thermal efficiency while remaining consistent with economic constraints in large-scale projects.

6. THE MAIN FINDINGS AND CONCLUSIONS OF THE STUDY

1- The experimental results confirm that air velocity plays a critical role in determining the thermal performance of the solar air collector. Increasing the air velocity from 1 m/s to 3.5 m/s significantly enhances convective heat transfer and useful thermal energy extraction.

2- At a lower air velocity of 1 m/s, a higher temperature rise between the inlet and outlet air was observed due to longer air residence time; however, this condition resulted in lower overall thermal efficiency because of reduced mass flow rate.

3- Increasing the air velocity to 2 m/s improved the balance between temperature rise and airflow rate, leading to a noticeable enhancement in useful thermal energy compared to lower velocity operation.

4- The highest air velocity of 3.5 m/s achieved the maximum useful thermal energy (up to approximately 200 W) and the highest thermal efficiency (around 57%), despite a relatively lower temperature difference, indicating more effective heat extraction under high-flow conditions.

5- The incorporation of porous media further enhanced the thermal performance by increasing the effective heat transfer area and promoting airflow mixing, which contributed to improved efficiency at higher air velocities.

6- Overall, the results demonstrate that optimizing air velocity is essential for maximizing the thermal efficiency and energy output of solar air collectors operating under real climatic conditions.

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