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Experimental Study of the Effect of Porous Media on the Performance of Single-Pass Solar Air Heater

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ABSTRACT

Solar energy is harnessed to heat the air, which is then utilised for warming greenhouses and drying crops. Solar air heaters may readily increase their performance using an absorbent plate design with a front pass of steel wools. This kind of SAH has been investigated and compared to a conventional flat absorbent plate. Steel wool, a cost-effective and permeable substance, possesses excellent heat conductivity, and it can be utilised in ongoing initiatives to enhance convection and thermal efficiency (ηth). The analysis in this research is based on data from experiments, focusing on the single-pass SAH technique and considering two scenarios: traditional system and porous system, with air mass flow rates of 0.015 Kg/s and 0.035 Kg/s. The experimental findings show that employing porous materials increases the exhaust temp by 12.28% and 21.32 % form of air 0.015 and 0.035 Kg/s, respectively. Moreover, the solar radiation readings for non-porous and porous medium SAHs were recorded as 905.32-912.92 and 979.04-945.6 W/m^2, respectively, at 1:30 p.m. Furthermore, thermal efficiency is between 33.29 % and 64.36 % in the porous scenarios and between 30.12% and 57.36% for non-porous cases. Porous media increases the thermal efficiency by 10 % and mass flow rate by 14 %.

1. Introduction

A solar air heater is a heat exchange system widely employed in situations with low temperatures [1,2]. The absorber plate is a crucial SAH element that converts solar energy to thermal energy. The primary drawback of SAHs is the poor heat transfer coefficient through the plate that absorbs radiation and the flowing air, which results from the air's thermo physical characteristics. Recent investigations have devised several methods to boost the efficiency of SAHs. The thermal energy produced by SAHs has a wide range of usages, including crop drying and heating of spaces for residential buildings during cold weather. Solar energy for air heating is much more environmentally friendly and economical than fossil fuels [3,4].

Utilising a steel mesh wire plate as an absorber and fins included the thermal performance of both SPSAH and DPSAH, as shown by Omojaro and Aldabbagh [5]. The study found that the thermal efficiency of Single-Pass Solar Air Heaters (SPSAH) and Double-Pass Solar Air Heaters (DPSAH), both

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utilising a layer of steel wire mesh as an absorber plate, surpasses that of conventional Solar Air Heaters (SAH). Additionally, double passes have an efficiency of 7–19.4% greater than single passes. Rashidi *et al.,* [6] reported the application of the porous material renewable energy systems. Observations reveal that porous materials can promote heat transmission, enhance thermal efficiency, minimise heat loss, provide more uniform temperature distributions, and enhance the performance of solar collectors. The photovoltaic/TW system's thermal and electrical performance has been improved by inserting a porous material, a fan, and a glass cove. Ahmed *et al.,* [7] theoretically and experimentally explored the PV/Trombe wall system. Their findings indicate that adding a porous material, a fan, and a transparent upper layer similar to glass boosts its thermal and electrical performance.

Mabrouk *et al.,* [8] examined the newest advancements in latent and sensible heat storage using porous material as a promising technology, giving energy storage researchers and engineers helpful knowledge. The research shows numerous strategies for storing thermal energy, including sensible, latent storage employing PCM and thermochemical heat storage, including LHS systems. Porous media enhances the thermal performance of systems in general, reduces energy usage, and lowers carbon dioxide emissions, all while maintaining comfortable temperatures in buildings. Ismail *et al.,* [9] investigated the construction of DPSAH containing lava rock. The measurements revealed that the DPSAH with lava rock, which used lava rock to store and promote heat transfer, performed better at transferring heat, according to measurements. The staggered or LFPSAH, as suggested by Abushanab *et al.,* [10], incorporates a specially designed aluminium alloy sponge for efficient thermal storage. By incorporating an aluminium sponge as a porous material, the staggered or LFPSAH set-up can maximise the daily energy efficiency enhancement of the convection heat transfer coefficient in the SLFPSAH, eliminating the medium. Such improvement could raise solar air collector performance in solar drying applications.

Theeb and Yousif [11] utilised several forms of porous material and barriers within SAHs. The results suggest porous materials and barriers in SAHs may improve heat transfer, system performance, and efficiency. The configuration of an energy-absorbing plate, comprising a wire mesh layer within a typical SPSAH, was investigated by Rasheed *et al.,* [12], who conducted experiments with a conventional absorber plate. The findings demonstrate that the newly suggested approach is superior in terms of thermal efficiency compared to the previous way. Additionally, it facilitates an even flow of air throughout the absorber, boosts the area, and improves heat transfer, raising the duct's surface temperature. Key factors such as mass flow rate, the absorber surface's geometry, and the solar radiation's intensity significantly impact the efficiency of Solar Air Heaters (SAH). Alomar *et al.,* [13] suggested layering a porous substance over a finned absorber plate. Results show the modified sample surpasses the standard by 7% across varying air mass flow rates. Sample 2 employs porous materials, while Sample 1 utilises conventional SAH. The measurement data was gathered in January 2021 in Mosul, Iraq. For mass flow rate = 0.02 kg/s, Model 2 has a maximum efficiency of 67%, followed by Model 1 at 60%. At a consistent mass flow rate, the updated system demonstrates a notable increase in exhaust temperature, with Model-2 outpacing Model-1. The rise in sample efficacy underscores the significant impact of porous materials on heat exchange, enhancing the heat transfer rate.

Mittal and Varshney [14] investigated the parameters that might affect heater performance, such as a wire mesh shape and mass flow rate. Dhiman *et al.,* [15] conducted practical and theoretical research on counter *and* parallel flow packed-bed collectors. The data indicates that counterflow in packed bed solar air heaters (SAHs) outperforms parallel flow by 11% to 17% in thermal efficiency, although parallel-flow collectors have shown a 10% boost in efficiency, akin to thermo-hydraulic thermal efficiency. Hernandez and Quiñonez [16] presented two analytical models to examine the thermodynamic parameters of collectors with counter and double-parallel flow configurations. Velmurugan and Ramesh [17] reported the presence of a 20-mm wire mesh positioned between the absorbent and the second cover made of glass. The study revealed that the efficiency of the SAH rose by 5% compared to the typical scenario. Saedodin *et al.,* [18] delved into solar porous metal collectors, and their proposal involves integrating a porous matrix in the solar energy collector to elevate its performance.

The current study included constructing and evaluating a solar air heater with a single pass design, which used an absorbent plate design with a front pass of steel wool. Steel wool is an inexpensive, porous material with great heat conductivity. The proposed solar air heater was also compared with a conventional flat absorbent plate at various mass flow rates.

2. Experimental Set-Up

2.1 Experimental Rig

This study conducted an experiment to investigate the thermal performance of a solar air heater (SAH) under two scenarios: a traditional absorbent plate and the same absorbent plate with porous media. The SAH and measuring devices are the main part of the experimental set-up. The experiments were conducted in Babylon, Iraq, experiencing winter throughout December, January, and February in 2023-2024. The geographical coordinates of Iraq are around 32.48389° latitude and 44.43111° longitude. Iraq's strategic position in the northern hemisphere makes it ideally suited for harnessing abundant solar energy. The inclination of this heater was intended to be appropriate for the specific degree of the nearby latitude. The inclination of SAH's slope has been adjusted to 47° south. Practical tests were conducted in cold weather from 9:00 a.m. to 4:30 p.m. The dimensions for air entrance and exit measures are 185 × 145 mm. The solar radiation transparent surface, made of glass, has dimensions of 2000 × 1000 mm and a thickness of 5 mm. The heat absorption plate is a metallic material with 2000 × 1000 × 0.5 mm dimensions. Wood was utilised as an insulating material for the bottom and two sides, with a thickness of 40 mm, whereas the absorbent plate was made of copper and coated in a dark black hue. Figure 1 displays the experimental set-up. Table 1 illustrates the characteristics of the SAHs.

(a) (b)

Fig. 1. Displays the experimental set-up for two scenarios of solar air heaters (SAHs): (a) the conventional SAH and (b) the SPSAH with porous media

When examining SAHs, there is a 7.5 cm difference in airflow through the surface of the absorbent plate and the outside of the glass sample, as well as in the space separating the surface of the absorbent plate and the bottom insulator. Steel wool is a porous material to enhance the convection process in SAHs. The steel wool was uniformly distributed throughout the airflow above the flat plate, and its properties are shown in Table 2. The airflow permeates the porous materials, facilitating heat exchange with them. Steel wools have an important degree of thermal conductivity, enabling the quick transfer of heat. Consequently, the air movement effectively facilitates heat exchange with the heated porous materials.

Furthermore, steel wools enhance uniformity within solar air heaters. This research project examined two scenarios: non-porous and porous SAHs. The scenario entails dispersing 500 g of steel wool uniformly. This set-up allows for observing transient dynamics and assessing SAHs that incorporate porous materials, gauging their efficiency and functionality.

Table 1
Characteristics of the SAHs

Items	Characteristics
Type of flow	Single-pass
Solar air heater box	2000 mm × 1000 mm × 150 mm
Insulator	20 mm wood
Absorber	copper, 2000 × 1000 × 0.5 mm
Glass	5 mm tempered glass, normally ironed, 95 % transmittance, 95 % Absorptivity
Coated absorber	28% Emissivity, 95 % Absorptivity
Fan	Cross-flow fan (220V, 1.0A)

Table 2
Steel wool Properties [19]

Physical Properties		
Description	Value	Unites
ρ	7900	(Kg/m^3)
Thermal Properties		
C_p	477	(J/Kg.C°)
K_s	14.9	(W/m.C°)

2.2 Experimental Procedure

The parameters under observation were recorded every thirty minutes during the study set-up. A 200 mm × 200 mm blower was utilised to facilitate air movement through the SAHs. The fan is perfectly designed to move air inside the SAHs, ensuring optimal heat transfer and circulation to airflow. Additional factors are utilised to determine the performance of SAH scenarios. The temperature at specific locations inside the system and on the plate that absorbs the radiation was also calculated, and temperature values can be obtained by utilising thermocouples positioned at various points along the SAH. The voltage regulator is connected to the air fan to regulate its speed and obtain variable values, enabling increased flexibility in affecting air flow rates during research. The thermal efficiency of the SAH design is evaluated at mass flow rates of 0.015 and 0.0035 Kg/s. The experimental set-up includes many measurement instruments to ensure the reliability and accuracy of collected data. The solar power metre measures the quantities and qualities of the incoming solar energy. Furthermore, the temperature recording data logger was utilised to record data gathered at regular intervals. The data logger records thermocouple temperature readings and other relevant information during the experiment. To analyse the data and evaluate the performance of each SAH configured, each scenario was tested two times on various days. The mean values were determined and compared to those obtained in the traditional scenario. Figure 2 explains the experimental work of the single-pass solar air heater.

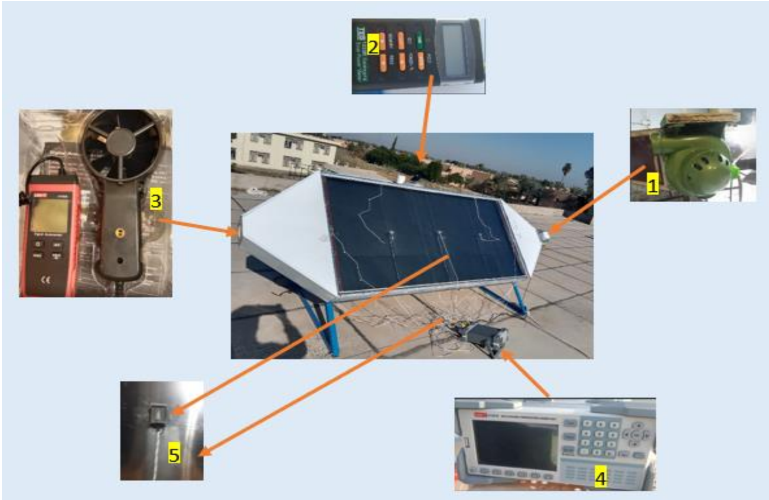

Fig. 2. Experimental work of single pass solar air heater for (1) air blower radial type, (2) solar power meter, (3) airflow meter, (4) the temperature recording data logger, and (5) thermocouples

3. Results and Discussion

Porous materials offer a practical approach to enhance the rates of thermal exchange in SAHs, and porous matrices can serve as substitutes. Due to the higher cost of porous matrices compared to materials like steel wool, the current study focused on exploring the potential of using steel wool to enhance convection heat transfer rates in SAHs.

Environmental parameters like sun intensity and ambient temperature majorly affect SAH performance. Experimental tests began at 9:00 a.m. and continued until 4:30 p.m. The ambient temperature ranges from 8.7 °C in the morning to approximately 24 °C around 2:00 p.m. Solar intensity significantly impacts the amount of energy a solar collector harnesses. The solar radiation was almost 310.62 W/m^2 at 9:00 a.m. and rose to 979.04 W/m^2 by 12:00 noon. Then it dropped to 0 at sunset. The experimental sessions extended until 4:30 p.m., nearly reaching sunset.

The variation in the profiles began to rise as the solar radiation increased; it also reached its peak when the solar radiation was greatest. The exhaust temp in flat plat SAHs and porous SAHs achieved a maximum temperature of 56.2 °C and 63.1 °C, respectively, with a mass flow rate of 0.015 Kg/s. The exhaust temp profiles followed the same arrangement as the two mass flow rates investigated, indicating the exhaust temp rose with increasing I and became highest when solar intensity reached its maximum level. In addition, in the afternoon, the temperature profiles decreased due to reduced solar radiation.

The observed data shows that utilising steel wools raised the maximum exhaust temperature by 12.28% and 21.32% for mass flow rates under the same ambient conditions. As a result, this strategy will be an effective and cheap method for producing elevated-temperature heat sources in SAHs. The data shows that increasing the mass flow rate decreased the exhaust temperature throughout a given day in scenarios. Given the situation, the exhaust temp decreased as the mass flow rate increased. Increasing the mass flow rate reduced air stay within the thermal collector, resulting in a lower exhaust temperature. Increasing the mass flow rate decreases air remaining within the collector, resulting in a lower exhaust temperature.

Figure 3 and Figure 4 depict the relationship between the external climatic conditions, solar radiation, and temperature for the air mass flow rate of 0.015 Kg/s. SAH recorded the maximum solar radiation value at 12:00 p.m. in the conventional system, measuring at 905.32 W/m^2. In contrast, using porous media resulted in a slightly higher value of 912.92 W/m^2 for SAH. The ambient temperatures indicated a similar pattern to solar radiation, increasing around 2:00 p.m.

Figure 3 and Figure 4 illustrate the variations in output air temperature at thirty-minute intervals for both scenarios, capturing the temperatures of the absorbent plate surface, ambient air, upper and lower air, and glass within the SAH at a mass flow rate of 0.015 Kg/s. The calculated temperatures of the exhaust temp flat plate SAH and the exhaust temp with steel wool SAH were 31.05-56.2°C and 38.3-63.1°C, respectively. While T_p varied between (49.4-87.4C° and 51.4-90.3C°), T_{up} air changed between (37.4-63.6 C°) and (49.2-76.2 C°), and T_{Low} air changed between (24.7-48.8 C°) and (27.4-50 C°) when ambient temperature increased. As estimated, the output calculated temperature of the solar air heater with steel wools is greater than in the traditional system.

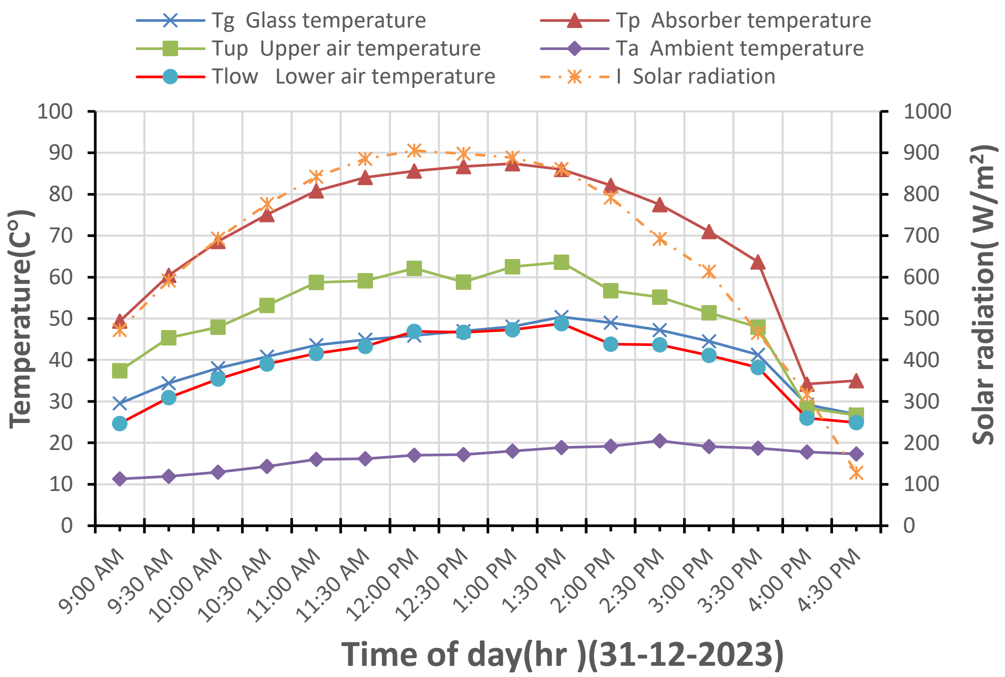

Fig. 3. Glass, absorber, upper air, lower air, ambient temperatures, and solar radiation versus standard local time of the day of SPSAH at m˙ = 0.015 kg/s

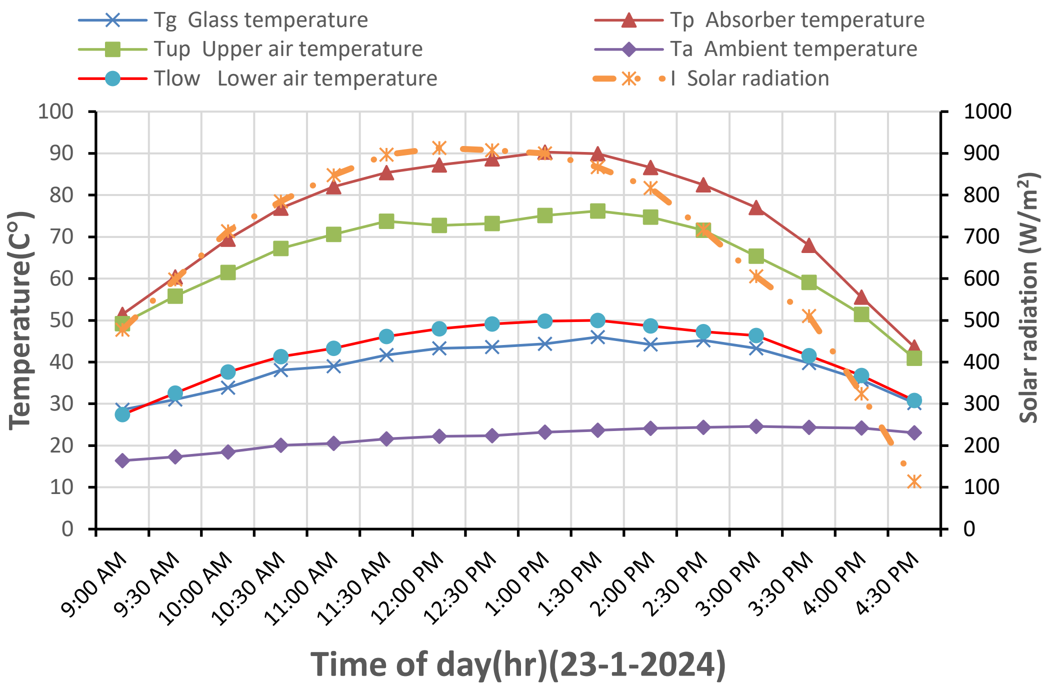

Fig. 4. Glass, absorber, upper air, lower air, ambient temperatures, and solar radiation versus standard local time of the day of SPSAHWP at ṁ = 0.015kg/s

Figure 5 and Figure 6 display the external climatic conditions for the second mass flow rate of 0.035 kg/s. The solar collector recorded the highest measured solar radiation value of 979.04 W/m^2 at 12:00 p.m. in the traditional system and 945.6 W/m^2 in the porous medium SAH. The ambient temperature reached its highest around 2:00 p.m. The temperature data for the two SAH models was recorded at the air mass flow rate of 0.035 kg/s. All recorded temp values represent identical behaviour. The higher values of T_o, T_p, T_{up}, T_{low}, and T_g of the conventional system and SAH with porous media are(26.05 C°-47.85 C°,32 C°-58.05 C°),(47.4C°-82.5C°,44.4C°-82.1C°),(32.3C°-54C°,42.3C°-75.2C°),(19.8C°-42.9C°,21.7C°-42.1C°), and (25.5C°-47C°), (25.5C°-47.8C°,25.4C°-60.9C°) respectively.

The temperature at the outflow of the porous media Solar Air Heater (SAH) exhibited a higher ratio than that of the Flat Plate Solar Air Heater (FPSAH). Moreover, the temperature within the porous media SAH surpassed that of the conventional system.

Figure 7 and Figure 8 present the variation between exhaust and ambient temperature from 9:00 a.m. to 4:30 p.m. for non-porous and porous media. The figures compare the difference due to different mass flow rates of 0.015 Kg/s and 0.035 kg/s. Non-porous SAHs have exhaust temperatures ranging from 56.2 °C to 47.85 °C. Porous media SAHs with mass flow rates (ṁ) of air 0.015 Kg/s and 0.035Kg/s have exhaust temperatures of approximately 63.1 °C and 58.05 °C, respectively. Meanwhile, using porous media raises the exhaust temperature by around 12.28 % and 21.32% when the mass flow rate is 0.015 Kg/s and 0.035 Kg/s, respectively.

The utilisation of porous media improves the effective thermal conductivity within the porous SAHs, thereby expanding the surface area for efficient heat transfer. Using steel wool as a porous material allows for higher exhaust temperatures when pores are present, compared to when there are no pores, over a 24-hour period. Due to the significant solar intensity, the exhaust temperatures of SAHs remain consistent during the beginning and end stages of the experiment.

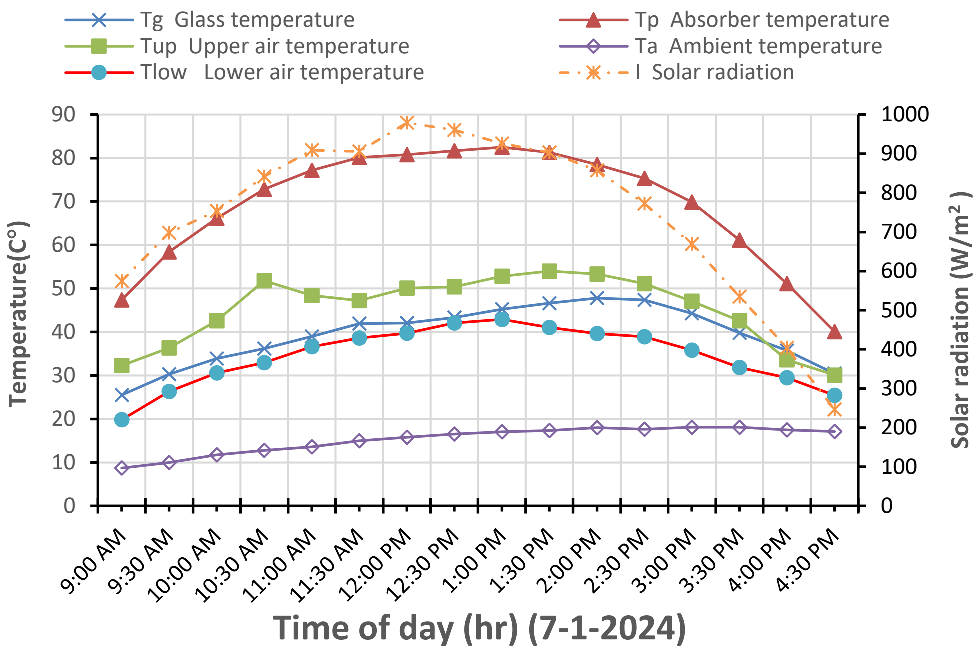

Fig. 5. The glass temperature, upper air temperature, lower air temperature, absorber temperature, ambient temperature, and solar irradiation at different times on 7/1/2024 for SPSAH at ṁ =0.035kg/s

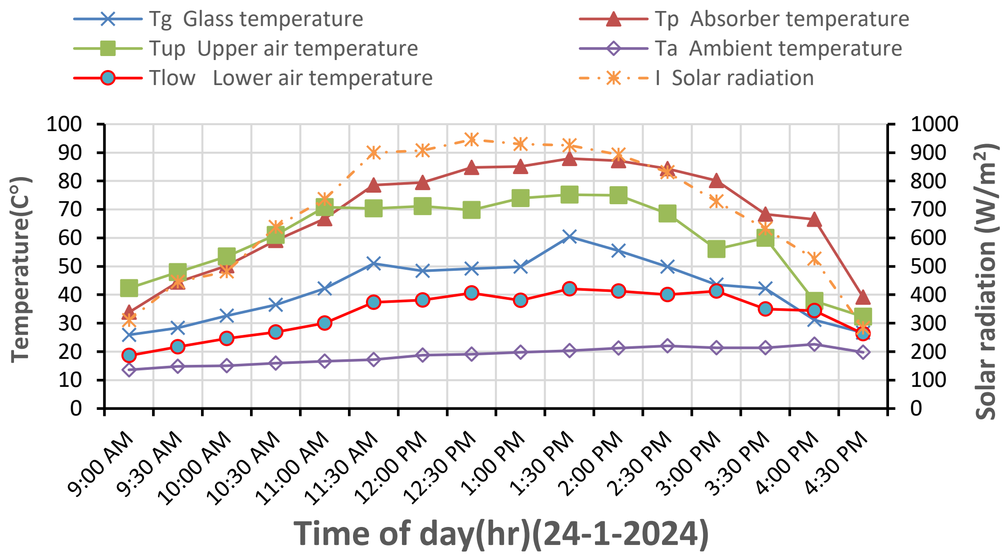

Fig. 6. The glass temperature, upper air temperature, lower air temperature, absorber temperature, ambient temperature, and solar irradiation at different times on 7/1/2024 for SPSAHWP at ṁ =0.035kg/s

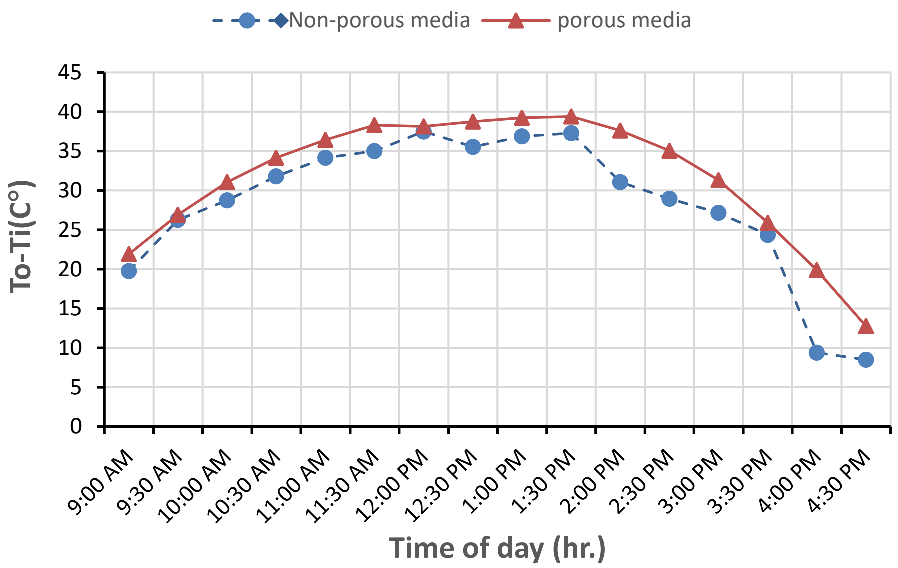

Fig. 7. Temperature Difference Variation with Time for SPSAH and SPSAHWP at ṁ = 0.015 kg/s

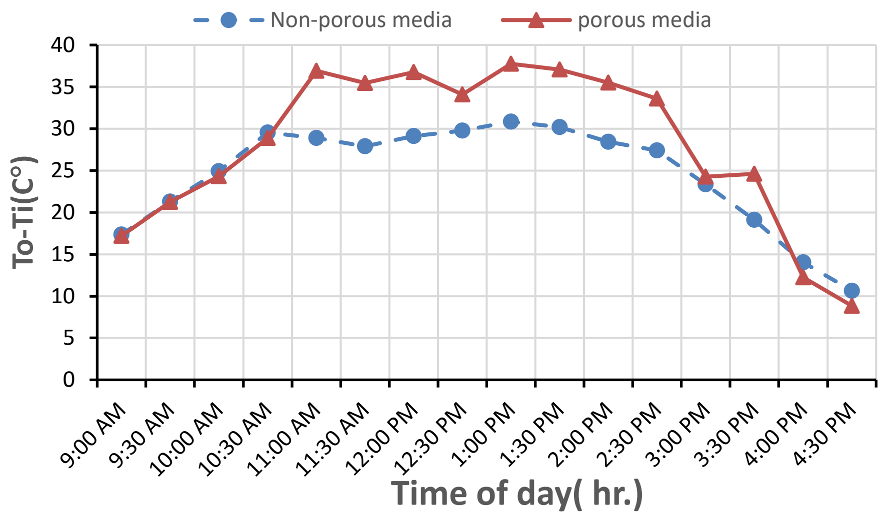

Fig. 8. Temperature Difference Variation with Time for SPSAH and SPSAHWP at ṁ = 0.035 kg/s

Notably, the air flowing across Scenario 2 will acquire greater heat than Scenario 1. The difference is due to the equality of porous material, which significantly impacts the heat transfer process. In Scenario 2, the greater extent of the contact surface between the air and the porous material allows for more efficient heat transfer. Additionally, porous material provides a way to conserve thermal energy.

With the rise in sunlight intensity, heat gains also increase, which decrease in the afternoon once they reach a certain level. Between 12:00 p.m. and 1:00 p.m., the set-up porous SAH gains approximately 591.69 W and 1327.85 W in 0.015 kg/s and 0.035 kg/s. The non-porous SAH only adds 565.31 W and 1085.15 W for air mass flow rates of 0.015 kg/s and 0.035 kg/s, respectively, throughout this time. Thermal efficiency increases with the amount of heat gained under the same climatic conditions. By increasing the air mass flow rates in the non-porous scenario, the daily thermal efficiency reaches 30.12% and 57.36%. However, compared to the non-porous situations, the thermal efficiency in the porous scenario increases to 33.29% and 64.36%, respectively, for air mass flow rates of 0.015 kg/s and 0.035 kg/s. These percentages are 10% and 14% higher. The calculated daily thermal efficiency confirms the efficacy of incorporating cost-effective porous materials, such as steel wools, in SAH to boost thermal efficiency and elevate exhaust temperature.

The calculations were conducted by considering the duct as a system governed by the following equation [20]

$$Q=\dot{m}Cp(T_o-T_i) \tag{1}$$

where
$\dot{m}$ = the mass flow rate (kg/s)
C_p = the specific heat of the air (kJ/kg.C°)
T_o and T_i = air temperature at the outlet and inlet (C°)

The trapezoidal rule has been used to calculate the daily useful energy (Qu) for SAH [21]

$$Q_{ud}=\sum_{ti}^{tf} \mathrm{Qut} = \mathrm{b}[\frac{Qu1}{2} + Qu2 + Qu3 + \cdots + \frac{Qun}{2}] \tag{2}$$

where
t = time increments = 1800 second
Qu = useful energy at t time

The efficiency of the SAH may be determined using the equation that follows [22,23]

$$\eta_i=\frac{Qu}{Ac\ I} \tag{3}$$

4. Conclusions

In this study, the solar air heater (SAH) was experimentally investigated using a flat plate absorber and a steel wool layer absorber at different air mass flow rates of 0.015 kg/s and 0.035 kg/s. The gathered data and verified outcomes lead to the following conclusions

i. Using inexpensive steel wools is a very productive method for boosting the thermal efficiency of traditional SAH. Steel wools may be used in technical applications, making this approach attractive to any SAH type.
ii. It enhances the homogeneity of airflow inside the absorbent, giving more surface area and faster heat transfer, leading to raised temperatures on the surface of the duct system.
iii. The newly suggested technique exhibits much higher thermal efficiency than the old method. The increase in daily thermal efficiency demonstrates the advantageous impact of steel wool. The utilisation of steel wool results in a rise of about 10 % and 14 % to the specified $\dot{m}$. It is noteworthy to highlight that the thermal efficiency can be increased by approximately 30.12% - 33.29 % and 57.36 % - 64.36 %, which corresponds to a 10 % rise for air mass flow rate 0.015 kg/s and a 14 % increase for air mass flow rate of 0.035 kg/s.
iv. Utilising porous materials leads to a rise in exhaust temperatures by 12.28% and 21.73% for total air flow rates of 0.015Kg/s and 0.035 Kg/s, respectively.

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