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# Exergy Analysis of Flat Plate Solar Air Heaters Having Obstacles and Filled with Wire Mesh Layers

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# Exergy Analysis of Flat Plate Solar Air Heaters Having Obstacles and Filled with Wire Mesh Layers

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**Abstract.** Two new experimental studies are presented in this research for improving the convection heat transfer and efficiency of flat plate solar air heater (SAH). An exergetic analysis is applied for evaluating the efficiency of a flat plate (SAH) with and without porous media. It was specially designed, low height bed filled with aluminium wire mesh layers and four aluminium longitudinal obstacles that increase the air path flow through the bed and the area of the absorber plate. Six wire mesh layers as an alternative of absorber plate, the layers had an internal diameter of 0.31 cm and a cross-sectional area of 0.22 cm × 0.22 cm. The wire mesh layers and the obstacles, improve the heat transfer from the absorber mesh layers in the moving air inside the heater. The plotted exergetic efficiency curves are a function of solar intensity, ambient temperature, bed temperature and temperature rise parameter ($T_o$-$T_i$/ I). These efficiency curves are in bed with and without porous media through different airflow rate. The results illustrate that the heater with porous media SAH is more efficient, from exergy point of view, then the heater without porous media. The maximum exegetic enhanced efficiency with and without porous media SAH in this study has been found to be 3.42 % and 5.16 %, respectively. These results correspond to the low airflow rate of 0.015 kg/s and 2.5 cm channel depth. A significant improvement in the exergetic efficiency discovered when comparing the proposed system with other conventional SAHs.

## 1. Introduction

A SAH converts solar energy into useful thermal energy. In general, SAH works as a heat exchanger that transfers heat to a working fluid i.e. Air. The thermal performance of a SAH is influenced by different factors, such as airflow rate, solar radiation, inlet temperature, heater type, absorption area and orientation [1]. Conventional SAHs mainly consist of a panel made of wood or other materials, an absorber plate placed inside the duct, a thin glazing or transparent plastic at the top as a cover, and air blowers. The hot air duct is thermally insulated on all sides except for the covered top. Solar air heating systems are suffering from the disadvantage of low thermal efficiency [2]. The performance can be improved by enhancing the heat gain from the sun in the passing air. One way is to increase the heat absorption area with an extended surface that acts as an absorber plate. Also, one can increase the heat gain by improving heat transfer coefficient with turbulence fluid flow supporters such as artificial roughness, fins, obstacles and baffles on absorber surface. Different configurations can be implemented to increase the absorber plate area. A wire mesh layers can be used for that, causing the turbulence to flow in an interior channel. Increasing the surface absorbing area results in an advantage of the more useful energy in the passing air. But it was also found to be a disadvantage since it increases the heat loss to the environment, transferred through the top glass cover. Thus, the optimum design of the SAHs should consider low thermal energy losses and high heat transfer rate. To balance the amount of the heat gained and lost, the second law of thermodynamics and exergy consideration is appropriate. Recently, the concept of exergy analysis has received a significant attention from

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researchers. It was applied to different thermal methods, but the exergy analysis approach is still a limited research [3], [4], [5]. Sahu and Prasad [6] employed scientific investigations, using the rib roughened absorber plates SAH with arc-shaped wire, the exergetic efficiencies ($\eta_{II}$) and ($T_o$-$T_i$/I) temperatures rise parameter were evaluated for different value of the Reynolds number and different rib roughness. Kurtbas and Durmus [7] constructed five special solar heater heaters where the absorption area fixed perpendicular to the bed. The exergy efficiency, thermal efficiency and friction loss factor for those five new heaters were estimated at different values of the Reynolds number. Ozturk and Demirel [8] practically investigated the exergy efficiency and energy efficiency using a packed bed with Raschig rings. Velmurugan and Kalaivanan [9], analytically and experimentally evaluated steady-state dimensionless exergy and thermal energy for three heaters: First, single-flow SAH; second, finned roughened dual-pass SAH; third, wire mesh dual-pass SAH at various solar intensities and airflow rates. Kalaiarasi et al. [10] Experimentally designed an absorber plate made of longitudinal copper strips filled with synthetic oil (Therminol-55) and welded to one another. The values of exergy analysis and energy analysis are found 49.4% and 18.25%, respectively, for m= 0.026 kg/s. Chamoli [11] studied the effect of changing optimization variables of flat plate solar system on the exergy efficiency. The optimum results for maximum exergy of inlet temperature, absorber plate area, mass flow rate, and fluid outlet temperature have been obtained. Velmurugan and Kalaivanan [12] performed studies for different absorber surface geometries (lower channel) such as roughened, v-corrugated, wire mesh, and finned, to improve the effectiveness of exergy and energy efficiencies. Akpinar and Koçyig [13] determined the efficiencies by using the second law of thermodynamics, comparisons were also made with the first law of thermodynamics. The highest efficiencies are determined for the heater with leaf-shaped obstacles absorbent. The results prove that energy and exergy efficiencies depend remarkably on the absorber surface geometry, solar intensity and the extension of the airflow path. A literature review showed that there is a shortage of experimental exergy analysis work involving the use of obstacles with package wire mesh as an absorber area for SAHs. Also, from previous renewable energy researchers, the theoretical and practical analyses on exergy are found to be less than that of the energy analysis [14]. Thus, this study focuses on experimental exergy analysis of with and without porous media SAHs with the specially designed absorber area. This design combines among First, longitudinal aluminium obstacles which are implemented to increase the path of air flow and the velocity in the lower air channel. Those obstacles will achieve improvement in the outlet temperature and the exergy efficiency of the heater. Second, porous media with low channel depth (2.5cm) is used to create large turbulent flow through the channel. A six wire mesh layers with four longitudinal obstacle, were tested and developed into an outdoor testing facility. The temperature rises of air, exergy efficiency, energy efficiency and temperature parameter ($T_o$ - $T_i$)/I, are determined at various solar intensities and airflow rates. The results are analyzed and shown an enhancement in output air temperature and exergy efficiency compared with previous researchers.

**Table.1**

| | **NOMENCLATURE** |
|---|---|
| $A_c$ | Absorbed area ($m^2$) |
| $C_{up}$ | Air specific heat (KJ/kg.K) |
| $Ex_{dest}$ | Destruction exergy (W) |
| $Ex_{in}$ | Exergy inlet (W) |
| $Ex_u$ | Exergyuseful (W) |
| $F_R$ | Heater heat removal factor |
| I | Solar radiation (W/$m^2$) |
| m | Air flow rate (kg/s) |
| Q | Volume air flow rate ($m^3$/s) |
| T | Average temperature of the air (°C), T=($T_o$- $T_i$)/2 |
| $T_a$ | Ambient temperature (°C) |

| | |
|---|---|
| $T_i$ | Inlet temperature (°C) |
| $T_o$ | Outlet temperature (°C) |
| $T_{bed}$ | Bed temperature (°C) |
| $\Delta T$ | Temperature difference, ($T_o$- $T_i$) (°C) |
| $\Delta T_{bed}$ | Temperature difference of bed, ($T_{bed}$- $T_i$) (°C) |
| $U_L$ | Overall heat loss coefficient (W/m$^2$. °C). |
| $\rho$ | Air density (kg/m$^3$) |
| $\Phi$ | Porosity. |
| $\tau_\alpha$ | Transmissivity- absorptivity. |
| $\eta_{II}$ | Exergy efficiency. |

## 2. Experimental Setup:

The flat-plate SAH was constructed in Baghdad, Iraq to perform the exergetic efficiency without porous media ($\eta_I$) and exergetic efficiency with porous media ($\eta_{II}$) experiments. A wood heater was utilized with a size of 1 m × 1.50 m and a depth channel with a height of 0.05 m (Figure 1). There are two rectangular openings on the up of right and left sides of the bed with an extent of 0.20 m × 0.025 m which proceed as an air flow entry. The design dimensions and operating parameters value present of Table 1 was used for this study. The wood heater base and frame were color matte black for absorbing a solar ray and improved the efficiencies. Heater sides were thermally insulated with the Styrofoam (thickness of 20 mm) except the top of the channel (glass cover). Ordinary one panel of glass was used on top of the bed as a cover for SAH, the glass cover with a thickness of 4 mm. Six aluminium mesh sheets with square voids of 0.22 cm × 0.22 cm were fitted in the space between obstacle. The distance between mesh sheets and glass cover 20 mm and all sheets are put parallel to the upper side and down on the glass cover. Aluminium mesh sheets, which corresponded to an overall porosity of 0.88, were painted black before installation. Four aluminium obstacles with 3 mm thick and 47 mm high are located across the solar heater to partition heater into five equivalent parts. Every obstacle (1.30 m long) is coated black before inserting in the heater. The rubber bands of 0.5 cm thick and 0.3 cm wide are fixed at the top of the obstacles, the band was used to prevent obstacles touching the glass cover (reduce heat loss), also the air can't pass above obstacles (forced air to move in a way same as shown in Fig. 1), thus air gained heat as it passed through the SAH bed. The Hot Wire Anemometer HT-9829, 60-90 mA was used to determine the amount of air passing through the heater [15]. A uniform flow was created through the sensor (Hot Wire Anemometer), plastic straw tubes with a length of 2.5 cm and a diameter of 0.46 cm were placed on both sides of the sensor site. A blower and vacuum power of 0.75 kW, model 135C16A was joined at a discharge side, five airflow readings were obtained between 0.015 and 0.035 kg/s. A speed of the fan was controlled by the inverter drive speed control model: SV008iC5-1, 5A, 0.01-400Hz.

## 3. Experimental Procedure:

A thermometer was hung underneath the heater for recording ambient temperature $T_i$ (inlet air). A calibration check confirmed an accuracy of ±0.5 °C. Six thermocouples (T-type) are calibrated and confirmed an accuracy of ± (0.4 % + 0.5°C), these thermocouples were distributed inside SAH system as two groups: Three thermocouples were used for measuring average air temperature that passing through the bed, $T_{bed}$= ($T_{bed1}$+ $T_{bed2}$+ $T_{bed3}$) /3, thermocouples preset inside the bed between wire mesh layers (not attached wire mesh layers). Other three thermocouples were used to measure the average outlet temperature, To= ($T_{o1}$+ $T_{o2}$ + $T_{o3}$)/ 3, $T_g$ mean temperature of passing air extremely near to the upper cover. Hot Wire Anemometer was measured air velocity. $T_{bed}$ and $T_o$, were obtained by using digital thermometers (EXTECH), model SDL200, an accuracy of ± (0.4 % + 1°C). Solar radiation was determined using a pyranometer located close to the bed (RK200-03 Pyranometer, Range: 0-2000w/m$^2$, SN:R18021068). The best position of the SAH heaters faced to south direction with an angle of 41˚, to maximize sun radiation concentrated on the upper heater. The air circulation period lasted 60 minutes, during that time solar radiation I, inlet temperature $T_i$ (the same as $T_a$), bed temperature $T_{bed}$, and outlet temperature $T_o$ be recorded.

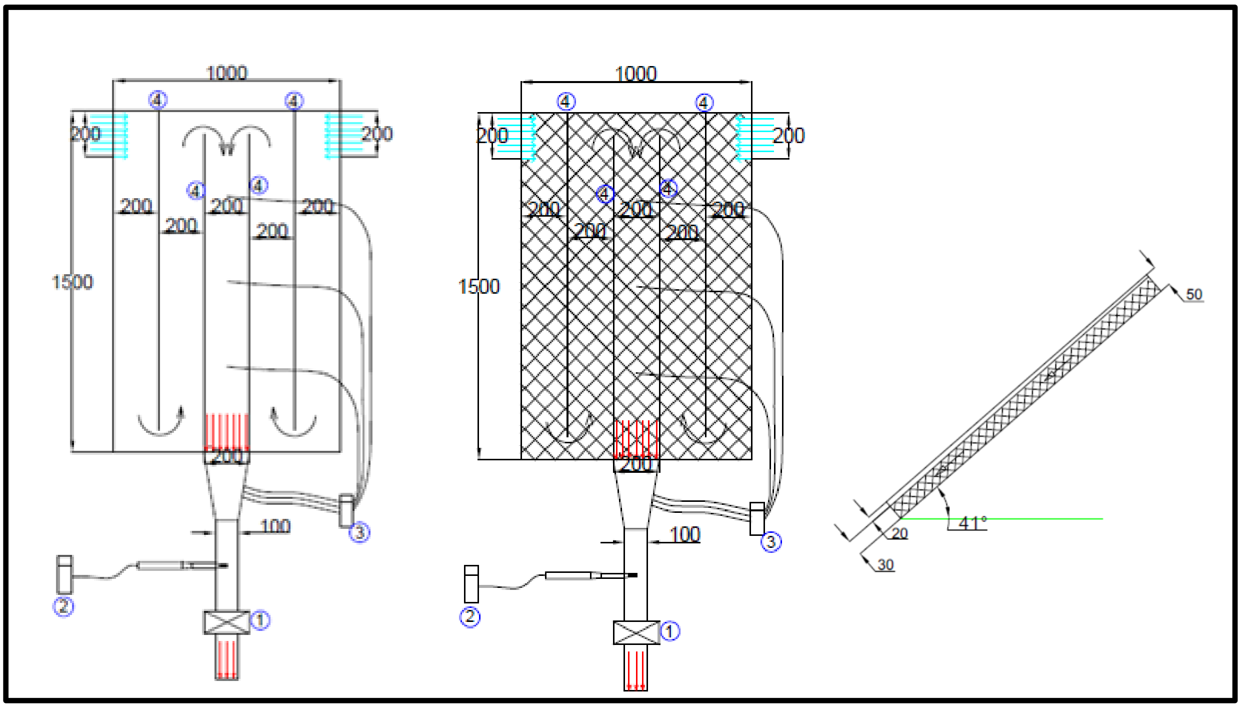



**Figure 1.** Assembly scheme of the SAH system, 4 obstacles for with and without wire mesh layers.1. Air blower, 2. Speed sensor, 3. Digital thermometer, 4. Obstacles.

## 4. Thermal analysis:

### *4.1. Energy Analysis:*

The performance of a SAH can be measured in terms of the heater thermal efficiency, which is expressed as the ratio of the useful energy gain divided by the incident solar radiation, given as (Jamadi et al. [1]):

$$\eta_{th} = \frac{m C_p (T_o - T_i)}{I \; A_c} \tag{1}$$

Umar et al. [16] determined an experimental equation for solving the thermal efficiency of a SAH system in terms of heat removal factor (FR), the equation is given as:

$$\eta_{th} = F_R \left[ (\tau\alpha) - (U_L) \frac{(T - T_a)}{I} \right] \tag{2}$$

The heat removal factor of the heater (FR) depends on the outlet air temperature and can be evaluated by Hottel–Whillier–Bliss equation:

$$F_R = \frac{m C_p (T_o - T_i)}{A_c [I(\tau\alpha) - U_L (T - T_a)]} \tag{3}$$

### *4.2. Exergy analysis:*

When applying the second law of thermodynamics, the performance of a SAH can be written in term of the heater exergy efficiency, which is defined as the ratio of the absorbed exergy of air ($EX_u$) to the input exergy of sun radiation ($EX_{in}$) on the heater [17]. Exergetic analysis is a useful method helps the designer to design SAH systems.

$$\eta_{II} = \frac{EX_u}{EX_{in}} = 1 - \frac{EX_{dest}}{EX_{in}} \tag{4}$$

Where (EXdest) are the exergy destruction (W). The parameters of equation (4) are presented as:

$$EX_{dest} = EX_{in} - EX_u \tag{5}$$

$$EX_u = \dot{m}\left[C_p\left(T_o - T_i\right) - T_a\left(C_v \ln\left(\frac{T_o}{T_i}\right) - R\ln\left(\frac{\rho_{out}}{\rho_{in}}\right)\right)\right] \tag{6}$$

The exergy of sun radiation (input exergy) is defined as [18]:

$$EX_{in} = \left(1 + \frac{1}{3}\left(\frac{T_a}{T_{sun}}\right)^4 - \frac{4T_a}{3T_{sun}}\right) I.A_c \tag{7}$$

$T_a$ refers to the ambient temperature, $T_{sun}$ almost 5600 K, refers to the solar intensity temperature [18].

## 5. Results and discussion:

Exergy efficiencies were calculated analytically using the commercial software Engineering Equation Solver (EES). The values of the system parameters (given in Table 1) and the operating parameters are used for solving the equations. This experimental study presents results and comparison of solar thermal systems, single-flow SAHs with 4 transverse obstacles and 6 wire mesh layers as a packed bed. The sun shines approximately 14 hours per day in June (Iraq- Baghdad city), 16.6 km/h wind speed (average hourly recorded mean value), and 21.5% relative humidity ratio (taken from the Met Office: Weather and climate change). Also, the average hour is recorded values of the solar intensity and the inlet temperature are 595 W/m$^2$ and 37.8 °C respectively. With this weather condition, the effect of solar radiation, inlet temperature, bed temperature, temperature parameter ($T_o$ - $T_i$)/I, and airflow rate of the exergetic efficiency was determined.

**Table 2.** Design dimensions and operating parameters value used for a study.

| Parameters | Values |
|---|---|
| Heater site | Baghdad, Iraq |
| Slope of the heater | 41$^o$ degree (33° 18 $^o$N and 44° 21 $^o$E) |
| Heater orientation | South |
| Length | 1.5 m |
| Width | 1 m |
| Depth | 0.05 m |
| Mass flow rate | 0.015- 0.035 kg/s |
| Styrofoam thickness | 20 mm |
| Mesh layer | Absorptive of 0.96, Emissivity of 0.87 |
| Number of glazing | 1 |
| Glass thickness | 4 mm |
| Speed | Wire Anemometer HT-9829, 60-90 mA |
| Blower and vacuum power | Centrifugal fan, 0.75 kW, model 135C16A |
| Pyranometer | RK200-03 Pyranometer, Range: 0-2000w/m$^2$, SN:R18021068 |

*5.1. The effect of solar radiation and inlet air temperature on exergetic efficiency:*

Variations of exergy efficiencies ($\eta_I$ and $\eta_{II}$) with average solar intensity and average inlet air temperature for single-flow SAH, with the time of the day from 8:00 am to 5:00 pm, using an airflow rate ranging 0.015 kg/s to 0.035 kg/s, are shown in Figure 2 (a-b).

The inlet temperature was an important factor that affected the exergy efficiency. The exergy efficiency clearly improved with the increase of inlet temperature related to equation (4). The exergy efficiency increases continuously from the morning at 8:00 am until it reaches a maximum value, between 1:00 pm and 2:00 pm then decreases until sunset. Based on the given the solar intensity and inlet air temperatures, 3.6% is a maximum exergy efficiency of the heater with wire mesh layers (WMLs) and 4.3% is a maximum exergy efficiency of the heater without (WMLs) at a low airflow rate (0.015kg/s). The maximum average values of the solar intensity (I) captured between 12:00 pm and 1:00 pm were 595W/m$^2$ and 615W/m$^2$ for with and without wire mesh layers SAHs respectively. While the average inlet temperature changes between 34°C to 40°C. Due to the clear sky conditions and stability of the climatic states (such as relative humidity and wind speed), solar intensity and inlet temperature values followed a similar pattern through the whole day of the work. This explains why the diagram of solar radiation and inlet temperature is drawn as an average reading (Fig.2) for all the days of the experiment. Although the solar intensity decreases after 1:00 pm, the exergy efficiencies continue to increase till 2:00 pm. The reason for that is the thermal energy received from the sun will be stored inside the wire mesh layers. Then, when the air moves through the heater to absorb the sun's energy it will additionally carry the heat from the wire mesh layers. For the bed with (WMLs), exergy efficiencies are greater than the bed without (WMLs), because the passing air was absorbed more heat from hot layers (layers heated from the sun) [2].

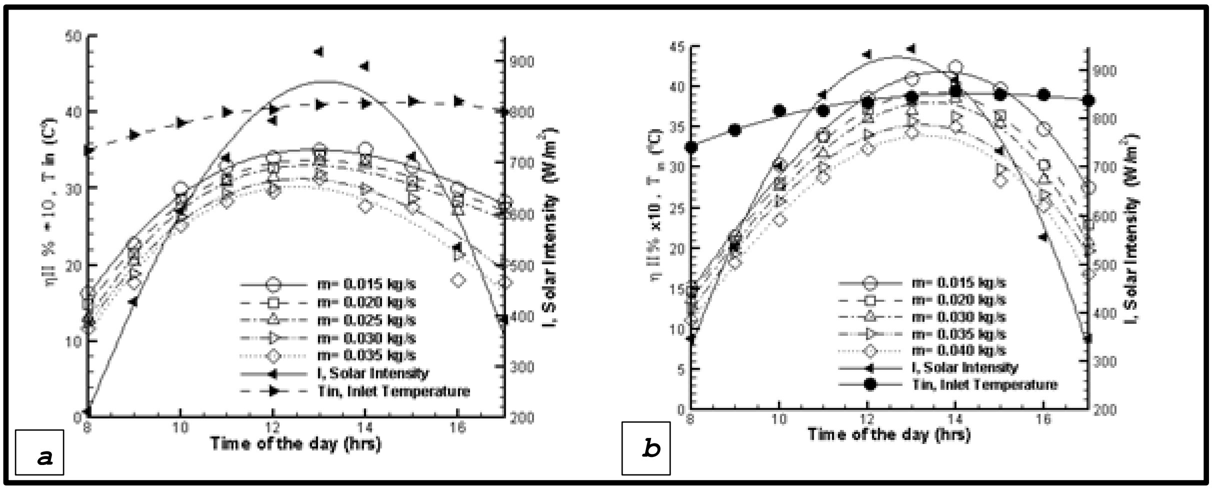



**Figure 2**. Solar intensity versus exergy efficiencies: (a) without wire mesh, (b) with wire mesh, during testing of the SAHs.

*5.2. The effect of bed temperature on exergetic efficiency:*

It was observed from Figure 3, that the maximum bed temperature difference $\Delta T_{bed} = T_{bed} - T_{in}$, with the time of the day is achieved for the airflow of 0.015 kg/s, 98 °C for heater with (WMLs) and 82 °C for bed without (WMLs), at 1:00 pm the highest exergetic efficiencies were produced.

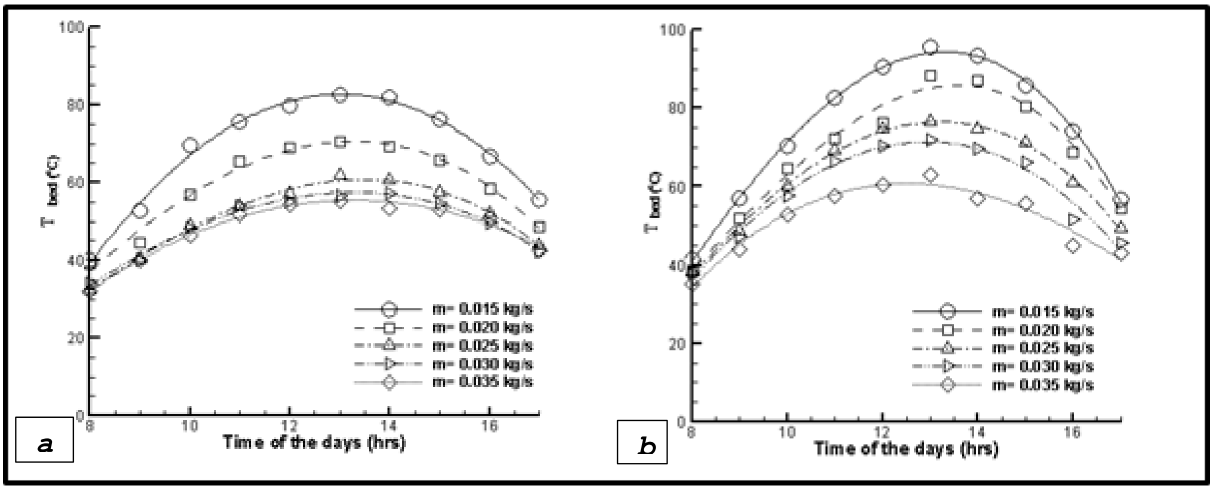
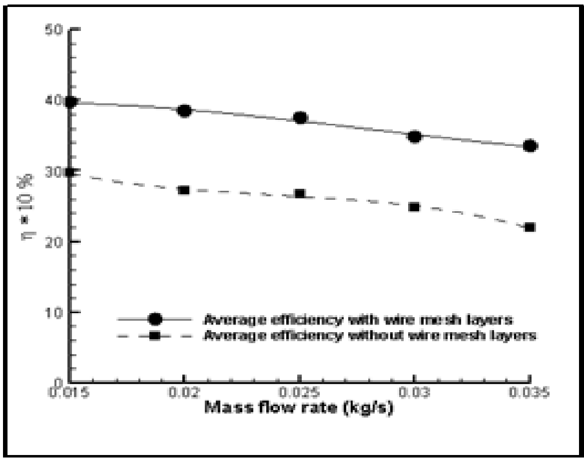



**Figure 3**. Temperature difference inside the heater with local time of the day, (a) without wire mesh, (b) with wire mesh.

The exergy efficiency versus the bed temperature for a SAH at airflow rate 0.015 kg/s undoubtedly increased with the rise of bed temperature. For SAH with (WMLs), the bed temperature and exergy efficiency are greater than for the without (WMLs) SAH at the same airflow rate (inlet air was heated from wire mesh, which caused the bed temperature to increase). Airflow rate of 0.015 kg/s (minimum rate) produces highest heater temperature and highest exergy efficiencies: The maximum values of Tbed and η were recorded to be 98 °C and 4.3 % for the SAH with (WMLs). At the minimum airflow rate, the air took more time to absorb heat energy than the maximum airflow rate to pass from the inlet part of the heater to the last part of the heater. Thus, passing air absorb additional heat from a wire mesh layer, which increase $T_{bed}$ and η.

*5.3. The effect of airflow rate of exergetic efficiency:*
Figure 4 presents the average exergy efficiencies versus different airflow rates. The exergetic efficiency goes on increasing in the range of airflow rate from 0.035 to 0.015 kg/s. Furthermore, the exergetic efficiency increases to a maximum value at the passing flow rate 0.015 kg/s, and at a higher passing flow rate, it starts decreasing. This happens due to the large exergy losses from the absorption of solar radiations by the wire mesh layers to the surrounding at a higher airflow rate. The SAH with (WMLs) was more efficient at all airflow rates compared to the SAH without (WMLs). The inlet air passes through the wire mesh between layers, so air temperature raises; which increasesuseful exergy gain and outlet temperature.

*5.4. The effect of temperature parameter (To - Ti)/I on exergetic efficiency:*
Figure 5 shows the variation of temperature parameters ($T_o$ - $T_i$)/I with the exergetic efficiencies of SAHs with and without (WMLs), at midday for airflow rate from 0.015 to 0.035 kg/s. The results show that exergetic efficiency increases with increasing ($T_o$ - $T_i$)/I. For SAH with (WMLs), the ($T_o$ - $T_i$)/I equal 0.048 °C.m$^2$/W at an airflow rate equal 0.035 kg/s, the highest exergetic efficiency was obtained. When the air passes between two obstacles or obstacles and edge of the bed, these small areas cause turbulent flow and separation flow, the separation flow will formulate a vortex on the back side of an obstacle. This phenomenon increases the heat absorption between wire mesh layers and the flowing air [19]. Which lead to an increment in both outlet temperature and the absorbed exergy, and decreases of heat transfer loss of the working fluid.



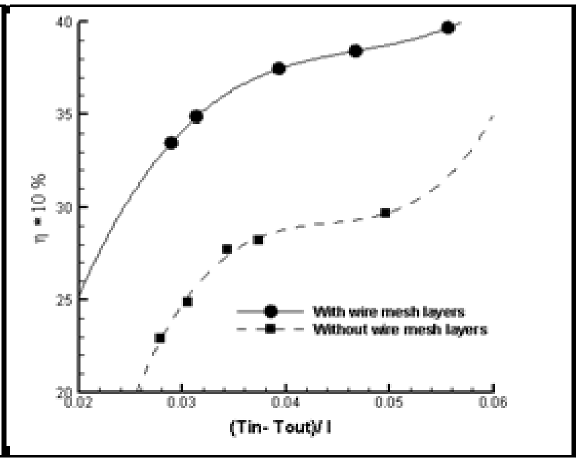




**Figure 4.** Mass flow rate versus exergy efficiencies.

**Figure 5.** Temperature parameter versus exergy efficiencies.

Figure 6 shows the variation of exergetic efficiencies (η) and thermal efficiencies (ηth) for with and without (WMLs) SAH as a function of airflow rate from 0.015 to 0.035 kg/s. It was observed from Figure 6, that the exergetic efficiencies go on increasing at low values of airflow rate (0.015 kg/s), and the average efficiencies of the SAH with (WMLs) are found to be bigger than the SAH without (WMLs). As decreasing airflow rate the absorption of solar radiations was increased, the heat transfer from the absorber wire mesh to passing air increased, the higher outlet temperature was materialized. Exergy loss due to absorption of irradiation by the wire mesh layers was decreased. Thermal efficiency has a different behavior than exergetic efficiency since it depends on useful energy gain and rate of heat transfer from the absorber wire mesh to passing air, thermal efficiency goes on increasing with the increase in airflow rate.

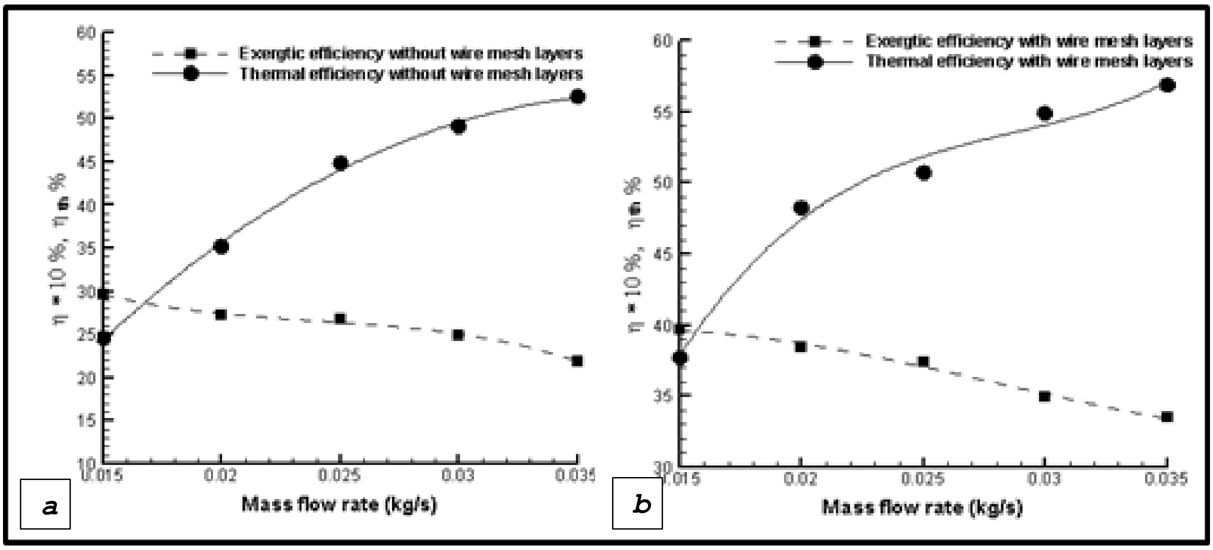



**Figure 6.** Exergetic efficiency and thermal efficiency and with airflow rate. (a) SAH without (WMLs), (b) SAH with (WMLs).

The comparison of the reported data with the present work shown in Table 3. The results demonstrate a significant improvement in the exergetic efficiency.

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**Table3.** Present work compared with other researcher SAH.

| Researcher | Type of SAH | Heater dimensions | Air flow rate (kg/s) | $\eta$ % × 10 |
|---|---|---|---|---|
| Esen [18] | Absorber plate with triangular obstacles | 1.25m× 0.8 m | 0.02-0.025 | 29.3- 25.6 |
| Deniz [20] | Fin obstacles | 0.63m× 0.32 m | 0.001- 0.006 | 4 -3.39 |
| Velmurugan [9] | Wire rib | 0.015-0.035 | 0.015-0.035 | 30-28 |
| Present work | Longitude obstacles and wire mesh layers | 1.47m× 1m | 0.015-0.035 | 43-36 |

## 6. Conclusion:

This experimental study predicted the exergetic efficiency of a solar air heater with wire mesh layers and without wire mesh layers having six wire layers and four aluminium obstacles as an absorber plate. The effects of solar radiation, inlet air temperature, bed temperature, temperature parameter ($T_o$ -$T_i$)/I and airflow rate, on exergetic efficiencies were specified.The solar intensity and inlet temperature are important factors, where the outlet temperature and exergy efficiencies depend on them. At high solar radiation and outlet temperature during midday, the exergetic efficiency and temperature parameter ($T_o$ -$T_i$)/I were increased. High thermal energy efficiency value is reached by raising the airflow rate, leading to high heat gain from the absorber mesh to the passing air. On the other hand, the exergetic efficiency will decrease by increasing the airflow rate, due to higher exergy losses from absorber mesh layers to environment by radiation and convection heat transfer. Additionally, results have been concluded that for solar air heater with wire mesh, the temperature of air passing through absorber layers is greater than those of the without mesh solar air heater at the same airflow rate. Finally, the longitude obstacles with wire mesh layers show an improvement in the exergy efficiency compared to other researches that used obstacles absorber solar heater types.

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