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Research Article

Evaluation of the Experimental Performance of an Asphalt Solar Air Collector

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ABSTRACT

In this research, the performance of an asphalt solar air collector was experimentally tested and the daily thermal and exergy efficiencies of the collector were analyzed. The sun's radiant energy is absorbed by asphalt and converted into thermal energy. Then, it is transmitted to aluminum pipes buried under the asphalt and, finally, to the air passing through the pipes. A suction fan induces the ambient air to the collector. The experimental results show that the daily thermal efficiencies at mass flow rates of 0.007 (kg/s) and 0.014 (kg/s) are 11.98 % and 24.10 % and daily exergy efficiencies are 0.34 % and 0.66 %, respectively, showing the increase in daily energy and exergy efficiencies with increasing the air mass flow rate. In addition, results show that as the flow rate increases, the outlet air temperature decreases. The presence of temperature difference between the inlet and outlet of the collector in the last hours of the day, when the sun's radiation is low, indicates that asphalt acts as a thermal energy storage medium.

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1. INTRODUCTION

Nowadays, due to the growth of energy demands in communities and the reduction of fossil fuel sources in the world, there is a tendency to use renewable energies. Among the various types of renewable energies, solar energy has received more attention in recent decades. One of the most important applications of solar energy is the production of electricity using solar panels and also the heating of various fluids such as air and water by solar thermal collectors. Solar thermal collectors are responsible for converting the radiant energy received from the sun into the thermal energy required to heat the fluid. Solar air collectors are used in many applications such as dryers, indoor heating, cooking, etc. [1]. Researchers are interested in solar air heaters because of their affordable cost, simple structure, and ease of construction [2, 3].

Asphalt and concrete solar collectors are very popular due to their ease of construction and good efficiency. The asphalt and concrete solar collectors are commonly used for water or air heating; so far, researchers have pursued different goals for the study of these types of collectors. Concrete Solar Collectors (CSCs) are a solar thermal technology for low-temperature applications. They are particularly suitable for integration on precast concrete clad buildings [4]. Asphalt solar collectors have better performance in energy storage and efficiency due to higher absorption coefficient and lower thermal conductivity than concrete collectors [5, 6]. A group of researchers by examining different types of pipe arrangements in asphalt collectors have tried to provide the best model of pipe placement to achieve the maximum performance of these types of collectors. In a laboratory study and numerical solution, Chiarelli et al. [7] discussed the arrangement, cross-sectional shape, and air volume of pipes in an asphalt air collector. In another study, Ehsan Hassan Zaim et al. [8] employed laboratory analysis and simulation of different models to investigate different arrangements of pipes in the thermal dynamics of an asphalt collector with water-working fluid. Then, they presented the best model for maximizing energy efficiency. Other studies have tried to investigate the effect of various factors on the efficiency of an asphalt solar collector such as the effect of using glass on the collector, the effect of solar radiation intensity in hot and cold seasons, and also the performance of the collector at different flow rates. In a study, Amirpooya Masoumi et al. [9] investigated the role of various factors in increasing the efficiency of an asphalt solar water collector in laboratory conditions. The results of this study in two cold and hot months of the year show that in general, the inlet temperature of the collector has a greater effect on increasing its performance than the surface temperature and conductivity of asphalt. Farzan et al. [10] experimentally investigated the effect of flow rate on the efficiency and dynamic behavior of an asphalt collector with water as working fluid. Results show that by increasing the flow rate, the thermal efficiency of the collector increases. In another experimental study by Farzan et al. [11], the effect of glass on the performance of an asphalt solar water collector was investigated, which showed the beneficial effect of using a glass shield on the collector

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surface. Studies on the pipes material in asphalt collectors show that metal pipes, which are often copper pipes, have a greater effect on increasing the performance of the collector than other materials [6]. In previous studies, the performance of asphalt collectors, which were often responsible for water heating, has been numerically and experimentally investigated, and few studies have only touched the issue of the operation and daily energy and exergy efficiency of an asphalt solar air heater in real conditions. Saad et al. [12] built a solar air heater with a free convection flow to investigate the effect of environmental parameters, such as ambient temperature and wind speed, on asphalt and outlet air temperature. In free convection flow, due to the low amount of flow rate, thermal efficiency is negligible.

To the best of authors' knowledge, experimental investigation of an asphalt air solar collector and evaluation of energy and exergy efficiency considering forced convection heat transfer have not been studied yet. In this research, an asphalt collector with 15 pipes and area of 1.4 m^2 has been tested for 8 hours during a day for two mass flow rates. The main objective of this study is to compare the thermal and exergy efficiencies of the asphalt solar air collector in a forced convection heat transfer regime. Based on the results for thermal and exergy daily efficiency as well as the output temperature of the collector at different hours of the day, the advantages of using asphalt solar air collectors can be realized further.

2. EXPERIMENTAL

In this experimental study, a wooden mold made of thick Russian wood was used. Russian wood is very suitable for outdoor use due to its high resistance to environmental conditions. On the other hand, due to its very low heat transfer coefficient, it does not easily transfer the heat stored in the asphalt layers to the environment and reduces the heat losses as much as possible. The asphalt used in this experiment is the commonly used asphalt in Iran. Thermophysical properties of asphalt are seen in Table 1 [8]. The substrate of this test is divided into two parts that are separated to be examined simultaneously for two flow rates. The area of each collector is 1.4 (m^2) and 15 aluminum pipes are buried at the asphalt depth of 3 (cm) in each collector. The inside and outside diameters of each pipe are 19 and 20 (mm), respectively. The pipes are installed at a distance of 2 (cm) from each other. Two sticks are placed between the two collectors so that the collectors are not connected. The complete geometric characteristics of the collector are given in Table 2. Schematic of the asphalt solar air collector is shown in Figure 1.

Table 1. Thermal properties of asphalt

k ($W/m^2.K$)	C_p (J/kg.K)	ρ (kg/m^3)	ε
1	1485	2450	0.95

Table 2. Asphalt solar collector specifications under investigation

Length of the collector (cm)	200
Width of the collector (cm)	70
Height of collector (cm)	20
Asphalt depth (cm)	8
Thickness of sand layer under asphalt (cm)	11
Buried depth of pipes from the asphalt surface (cm)	3
Distance between pipes (cm)	2
The inner diameter of pipes (cm)	1.9
The outer diameter of pipes (cm)	2
Number of pipes per collector	15

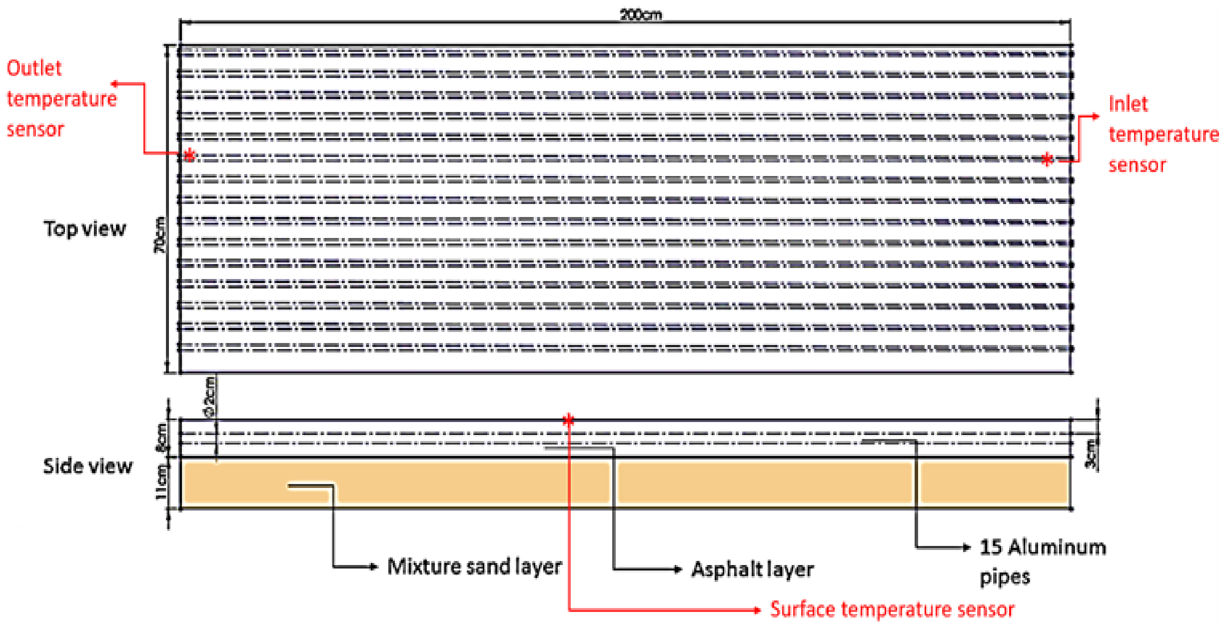

Figure 1. Schematic of the asphalt solar air collector

2.1. Test conditions

The test site was located in Kerman where the external factors such as trees and surrounding buildings do not affect the performance of the collector. Latitude and longitude in this place are 57.08 E and 30.28 N. The experiments were performed from 9 AM to 5 PM on November 3, when the ambient temperature is relatively low. The Kipp & Zonen pyranometer model CMP 6B was used to measure the amount of total solar radiation. The intensity of the sun's rays is recorded every 15 minutes. Measurements at short intervals give a better comparison between the energy entering the collector by the sun and the energy leaving it by the air. An exhausted fan induces the ambient air into the collector.

Velocity measurement was done by an anemometer-type BENTECH GM816A and two desired flow rates were achieved by the changing outlet area. The flow rates considered in this experiment are 0.014 (kg/s) and 0.007 (kg/s), which change slightly due to a small change in the output density with time during the day and can be considered constant. For temperature measurements, temperature sensors TM1321 are used. The measurement accuracy for this sensor is up to three decimal places. Temperature sensors are used to measure the temperature of the surface of the asphalt as well as inlet and outlet air temperatures of the collector at any time, and they are recorded by connecting sensors to a computer. There is a temperature distribution on the collector surface; thus, the sensor at the surface temperature was placed at the center of the collector. The asphalt solar collector under consideration is shown in Figure 2. Pyranometer and temperature sensors are seen in Figures 3 and 4, respectively.

Figure 2. The asphalt solar collector under consideration

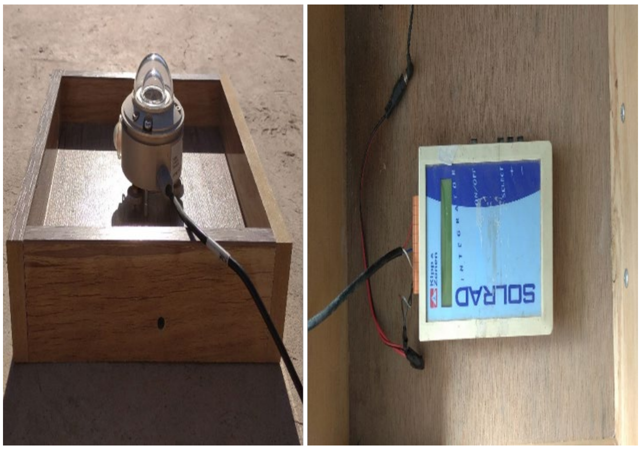

Figure 3. Pyranometer for measuring the intensity of solar radiation

Figure 4. Temperature sensor and transmitter type TM-1321

2.2. Uncertainty

Examining uncertainty in empirically conducted research is a very efficient and useful tool for calculating the number of errors in the results. The results extracted by the experiment may be subject to some errors, the main factor of which can be considered the accuracy of the measuring instrument. To obtain the amount of uncertainty during the experiment, Equation (1) is used [13].

$$w_R = [\sum_{i=1}^{n} (\frac{\partial R}{\partial x_i} w_{xi})^2]^{1/2} \quad (1)$$

In this equation, R is a non-independent quantity and x is an independent quantity. w_R and w_{xi} are the uncertainties for the quantities R and x, respectively.

The results of uncertainty along with the relative error based on the mean values defined by Equation (2) are seen in Table 3 [14].

$$E_R\% = \frac{w_R}{R} * 100 \quad (2)$$

Table 3. Relative errors and uncertainty of experimental data

Quantity	Uncertainty	E_R (%)
Temperature difference (°C)	± 0.1414	0.8
Mass flow rate (kg/s)	± 0.0009	6.3
Intensity of solar radiation (W/m^2)	± 5	0.6
Thermal efficiency (%)	± 0.010	5
Exergy efficiency (%)	± 0.012	0.2
Fan power consumption	± 0.04	3.8

Also, a graphical illustration of error bars is presented in Figure 5.

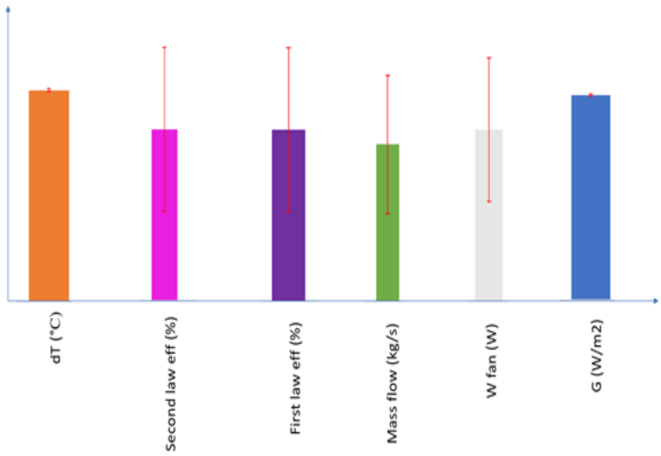

Figure 5. A graphical illustration of error bars

2.3. Thermal efficiency

To obtain the daily thermal efficiency of the collector, according to Equation (3) [15, 16], the values of inlet and outlet temperatures as well as the amount of solar radiation are needed. The amount of heat transfer into the air can be quantified by Equation (4). Due to the power consumption by the fan, this amount of electrical energy must be subtracted from the thermal energy by the fluid. For this reason, Figure 7 shows that the temperature difference decreases with increasing flow rate, but increasing the flow rate increases the thermal efficiency of the collector [10]. In Figure 7, it is clear that the maximum temperature difference is about one hour after the maximum intensity of solar radiation. Besides, the existence of temperature differences at the last hours of the day is an important result that demonstrates the ability of asphalt to store heat and to use this energy when the amount of solar radiation decreases.

$$\eta_{th,daily} = \frac{\sum \dot{q} - \sum \dot{E}_{el,fan}}{\sum G * A_C} \tag{3}$$

$$\dot{q} = \dot{m} C_p (T_{out} - T_{in}) \tag{4}$$

The pressure drop to be compensated by the fan can be calculated by Equation (5) and the consumed power by the fan can be obtained by Equation (6) [17]. The electrical power consumed by the fan is 1.1 (W) for the mass airflow rate of 0.014 (kg/s) and 0.36 (W) for 0.007 kg/s), respectively.

$$\Delta p = \frac{fl\rho v^2}{2D} + \frac{kv^2}{2} \tag{5}$$

In Equation (5), f was considered 0.039 and 0.041 for mass flow rate of 0.014 (kg/s) and 0.007 (kg/s), respectively. Also, k = 1.5[17].

$$\dot{E}_{el,fan} = \frac{\dot{m} * \Delta p}{\rho * \eta_{fan}} \tag{6}$$

Here, η_{fan} is fan efficiency which is 70 %.

In order to equalize the electrical energy consumed by the fan to thermal energy, an equivalence coefficient is employed. This factor is defined by Equation (7). The value of this coefficient depends on many parameters and factors such as the renewable energy market, exergy, greenhouse gas coefficients, and the number of fossil fuels in the country. According to Coventry and Lovegrove's research [18], this numerical value is between 1 and 17, such that the coefficient 1 is for energy efficiency and by increasing this value, it approaches the exergy efficiency. In Iran, according to the parameters of the renewable energy market, this amount can be considered as 4 [16].

$$r = \frac{\dot{E}_{el}}{\dot{E}_{th}} \tag{7}$$

2.4. Exergy efficiency

Due to the electrical energy consumed by the fan, the exergy loss by the fan should be subtracted from the useful exergy to the net pure exergy. The fluid entering the collector is ambient air; therefore, it has no exergy and only the input exergy to the control volume is supplied by solar radiation, which can be calculated by the patella relation given by Equation (8) as in the following [19].

$$\dot{E}_{in,sun} = GA_C\left(1 - \frac{4}{3}\frac{T_a}{T_{sun}} + \frac{1}{3}\left(\frac{T_a}{T_{sun}}\right)^4\right) \tag{8}$$

The useful exergy of the air can be calculated from Equation (8) [20].

$$\dot{E}_u = \dot{m} C_p \left[T_{out} - T_a - \left(T_a * Ln\left(\frac{T_a}{T_{out}}\right)\right)\right] \tag{9}$$

The net useful exergy is the difference between the amount of useful exergy and the fan exergy destruction. By using Equation (10), fan exergy destruction can be obtained by [17]:

$$\dot{E}_{dst,fan} = \frac{T_a}{T_F} \dot{E}_{el,fan} \tag{10}$$

In Equation (10) $\dot{E}_{el,fan}$ is the fan power, the value of which is 20 W. T_a is the ambient temperature and T_F is the temperature of the fluid, which is obtained from Equation (11) [21].

$$T_F = \frac{T_{out} - T_{in}}{Ln\left(\frac{T_{out}}{T_{in}}\right)} \tag{11}$$

The net useful exergy can be obtained by Equation (12) [22] as follows:

$$\dot{E}_{u,net} = \dot{E}_u - \dot{E}_{dst,fan} \tag{12}$$

Finally, the daily exergy efficiency of the collector can be determined by Equation 13 as follows [22]:

$$\eta_{exe} = \frac{\Sigma \dot{E}_{u,net}}{\Sigma \dot{E}_{in,sun}} \tag{13}$$

3. RESULTS AND DISCUSSION

The main purpose of this research is to investigate experimentally the performance of an asphalt solar air collector in terms of energy and exergy efficiencies. The affecting parameters can be categorized into environmental and construction ones. Environmental parameters include the amount of incident radiation on the collector surface, wind speed, and ambient temperature, which is the inlet temperature to the collector. The most important construction parameters are the materials used in the construction of the collector, pipes, and insulation. In the present study, asphalt has been used as the main material in the construction of the collector, which can absorb and store high thermal energy. Low-thickness aluminum has been selected for the pipe material, which increases the heat transfer coefficient to the airflow inside the pipes. In addition to their high heat transfer coefficient, the use of aluminum pipes is more advantageous over copper ones because it is lighter and cheaper. Figure 6 shows the variation of ambient temperature and solar radiation intensity during a typical day.

Figure 7 shows the temperature difference between the inlet and outlet of the collector. It is seen that the temperature difference is reduced by increasing the flow rate, but increasing the flow rate increases the thermal efficiency of the collector [10]. The maximum temperature difference is about 25 K and 19 K for the mass flow rates of 0.007 kg/s and 0.014 kg/s, respectively. In Figure 7, it is also clear that the maximum temperature difference is about one hour after the maximum intensity of solar radiation. Besides, the existence of temperature differences at the last hours of the day is an indication of the asphalt ability to store heat.

According to the results obtained from the collector efficiency in Table 4, it can be seen that by increasing the flow rate, both thermal and exergy efficiencies increase.

Figure 8 shows the variation of the surface center temperature of the collector during a typical day at two mass flow rates.

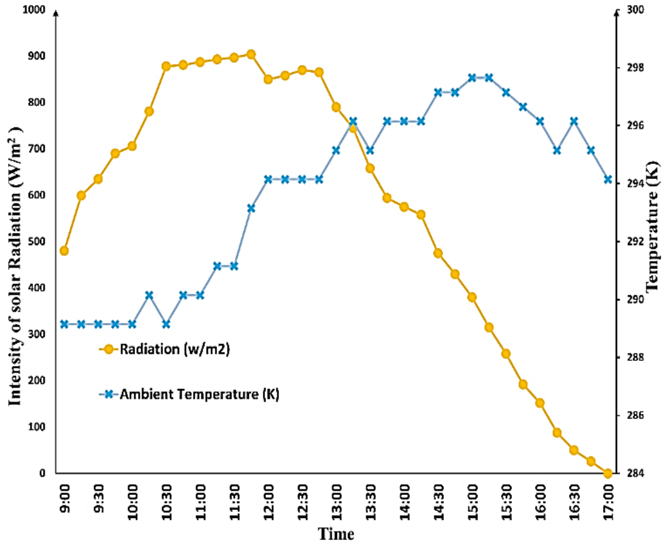

Figure 6. Ambient temperature and solar radiation intensity (2021/11/03)

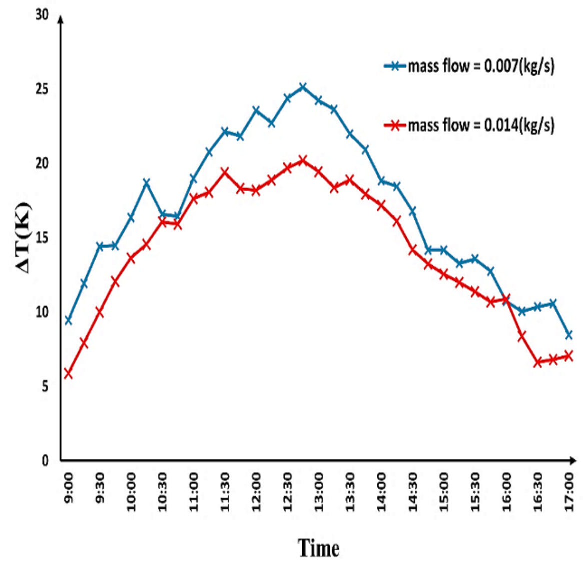

Figure 7. Variation of collector inlet and outlet temperature difference

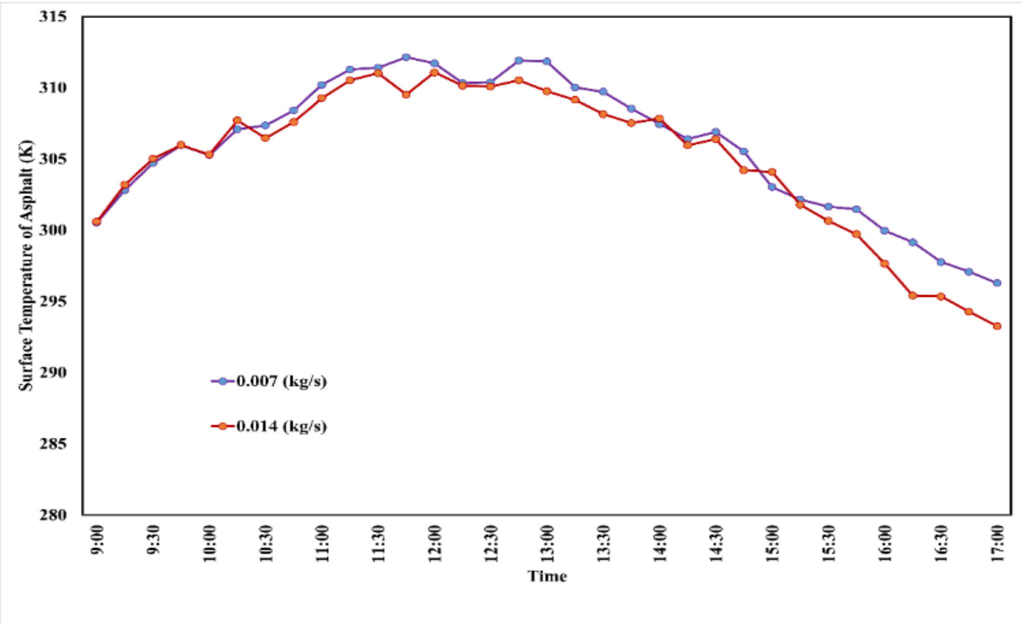

Figure 8. Variation of the surface center temperature of the collector

A better understanding of the exergy efficiency is secured by comparing the values of exergy obtained in each part. The amounts of useful exergy of the fluid and the exergy destruction of the fan are quite smaller than the amount of exergy input by the solar radiation, hence low exergy efficiency. Figure 9 shows the input exergy from the sun. Figures 10 and 11 show the comparison of useful exergy, net useful exergy, and exergy destruction of the fan at mass flow rates of 0.014 kg/s and 0.007 kg/s, respectively. According to Figure 10 and Figure 11, at the final hours of the experiment, when the sun's radiant energy is low, the net useful exergy is very low. By comparing the results in Figures 10 and 11, it can be seen that lowering the flow rate reduces electricity consumption and subsequently decreases the exergy destruction, which makes the net useful exergy higher at the final hours. Since the useful exergy is dependent on the outlet temperature, its value tends to zero at the end of the day. Therefore, it can be concluded that the best hours to keep the fan on are the hours when the sun radiation is not very low.

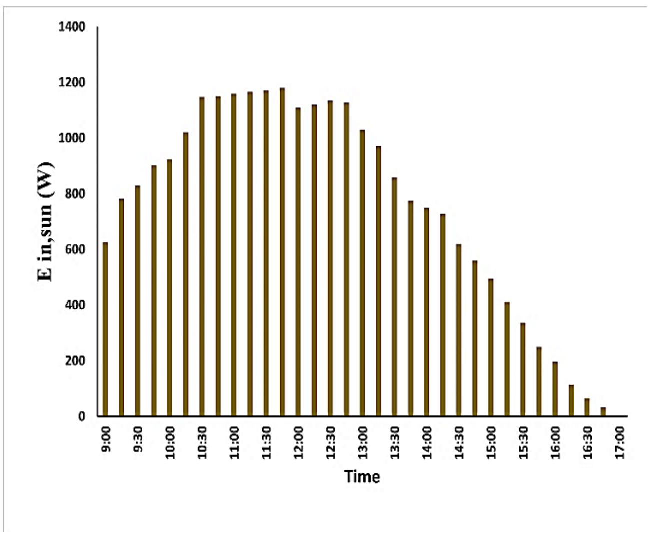

Figure 9. Input exergy of solar radiation

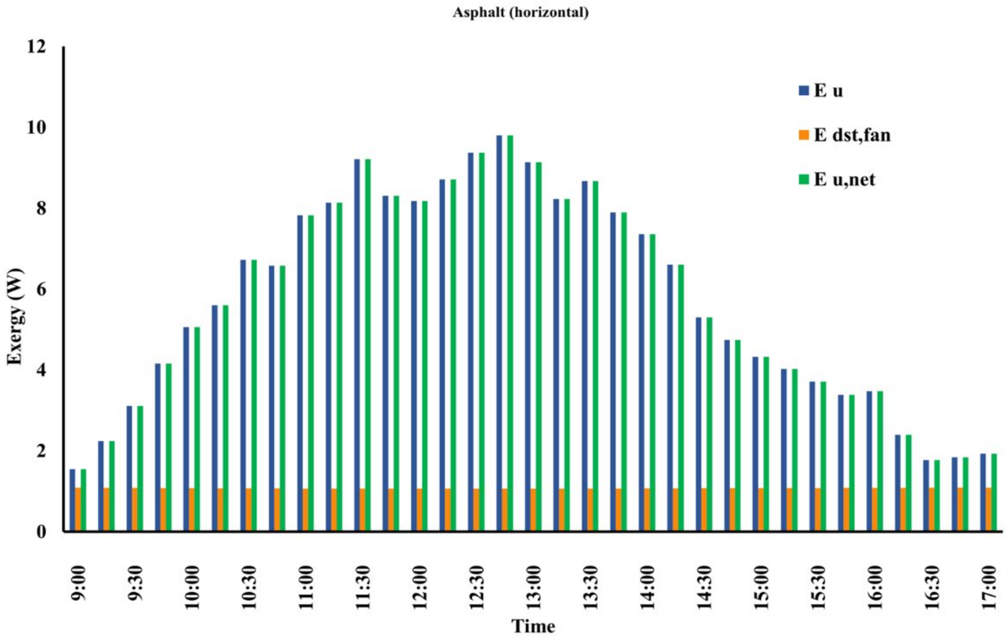

Figure 10. Comparison of useful exergy, net useful exergy, and exergy destruction of the fan for ṁ=0.014 (kg/s)

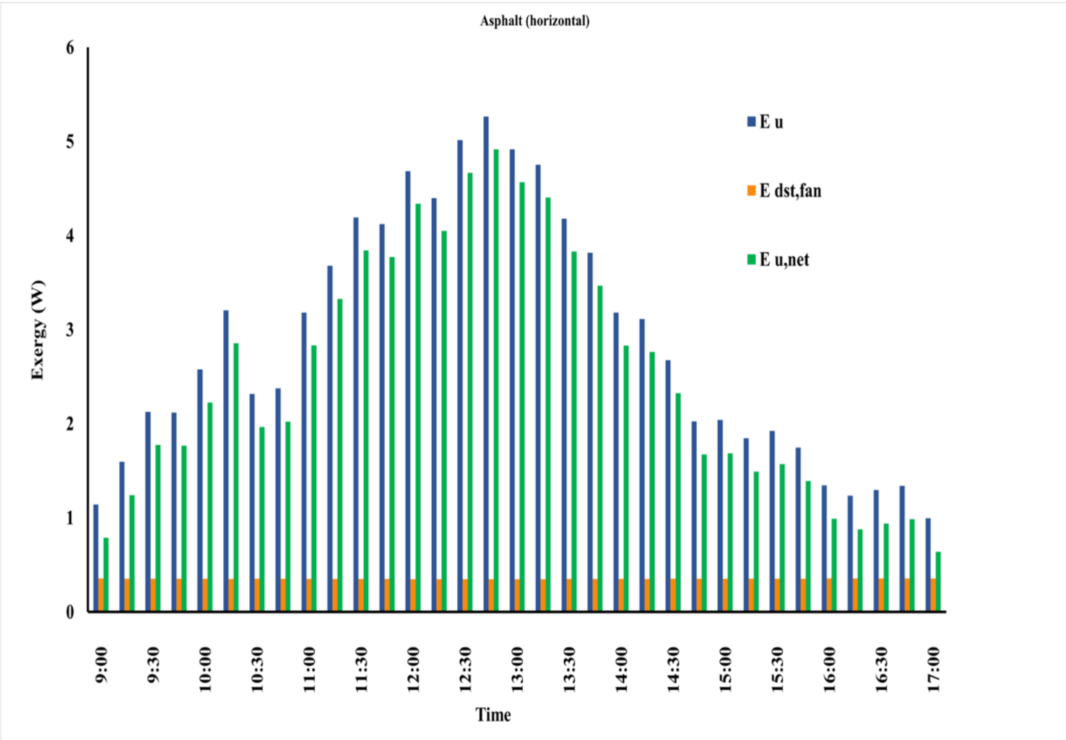

Figure 11. Comparison of useful exergy, net useful exergy, and exergy destruction of the fan for ṁ=0.007 (kg/s)

Table 4. Daily thermal and exergy efficiency of the collector

$\dot{m}$ (kg/s)	$\eta_{th,daily(no-fan)}(\%)$	$\eta_{th,daily}(\%)$	$\eta_{th,daily,r=4}(\%)$	$\eta_{exe,daily}(\%)$
0.014	24.24	24.10	23.66	0.66
0.007	12.03	11.98	11.85	0.34

4. CONCLUSIONS

In this research, an asphalt solar air heater was tested experimentally at two different flow rates. The final results of this research included the energy and exergy efficiency on a daily basis as well as the outlet temperature of the collector. The obtained results can be listed as:

- Increasing air mass flow rate increases thermal and exergy efficiencies.
- The presence of temperature differences at the last hours of the day and even after sunset indicates the ability of asphalt in storage and releasing heat when there is no radiant energy source.

- In the process of calculating the exergy efficiency on a daily basis, to obtain the net useful exergy, we subtract the amount of exergy destruction by the fan from the useful exergy of the collector. Exergy efficiency starts to decrease when the sun radiation decreases, given the reduction of the amount of exergy entering the collector.

As a result, to design an optimal collector, both the efficiency factor and the outlet temperature must be considered simultaneously so that we can have a high outlet temperature by having a collector with proper efficiency. Also, from the results obtained from exergy calculations, two cases can be considered for improving the collector efficiency:

- Setting a time interval for the fan to be on or off
- Using variable flow rate during the day

For further research, glazing of the collector is recommended. Also, it is recommended that a simulation by CFD be conducted to investigate the effect of different parameters on the performance of the collector.

5. ACKNOWLEDGEMENT

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NOMENCLATURE

A	Area (m^2)
G	The intensity of solar radiation (W/m^2)
C_p	Specific heat capacity (kJ/kg.K)
$\dot{q}$	Thermal energy transferred by the fluid (kJ/s)
$\dot{E}$	Exergy (W)
T	Temperature (K)
r	Equivalence coefficient
R	Non-independent parameter
x_i	Independent parameter
w	Uncertainty
f	Friction factor
l	Length of each pipe (m)
Δp	Pressure drop (Pa)
D	Outlet diameter (m)
v	Velocity (m/s)
ρ	Density (kg/m^3)
ε	Emissivity
Greek letters	
η	Efficiency
Indices	
c	Collector
a	Air
in	Inlet
out	Outlet
F	Fluid
el	Electrical
th	Thermal
fan	Fan
sun	Sun
dst	Destruction
exe	Exergy
u	Useful
net	Net
daily	Daily
eq	Equivalent

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