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# Effectiveness of Continuous and Discontinuous-Flow Strategies in Heat Dynamics and Performance of Asphalt Solar Collector: An Experimental Study

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Asphalt solar collectors (ASCs) offer a low-cost and reliable alternative to harvest energy from available infrastructures such as roads and pathways by employing the simple techniques. This paper represents an experimental study to evaluate the effectiveness of continuous and discontinuous-flow strategies in the dynamics and performance of a self-constructed ASC under field conditions. To this aim, an ON/OFF switching controller commands to run and stop the system at different time intervals. During the experimental simulations, all the crucial environmental and operational parameters were measured and monitored. This approach assesses the effects of numerous scenarios with different intervals of time on the dynamics of the constructed collector. Continuous and discontinuous-flow strategies were evaluated by comparing three different scenarios, including continuous-flow mode, 5 min OFF-mode and, 10 min OFF-mode. The results show that by extending the OFF-mode, the water is kept stagnant in the hot embedded pipes for more extended periods. Therefore, the temperature difference at the inlet and outlet of collector reduces, and the water leaves the collector at higher temperatures; however, the efficiency of the ASC decreases. Also, even though extending the OFF-mode results in heated water exits the collector at higher temperatures, but the mass of heated water decreases due to continuous interruption of current flow. The test results prove that in continuous-flow strategy, cumulative heat gain improves. Therefore, the continuous-flow strategy shows higher performance than introduced discontinuous-flow strategy. The exergy analysis illustrates that the available useful exergy has significantly affected by considering the pump consumed energy.

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## Nomenclature

| | | | |
|---|---|---|---|
| $A$ | collector area, $m^2$ | $X$ | exergy, $J$ |
| $c_p$ | specific heat capacity, $J/kg.K$ | | **Greek Symbol** |
| $B, C$ | constant values | $\alpha_s$ | solar absorption coefficient |
| $G$ | solar irradiation heat flux, $W/m^2$ | $\varepsilon$ | emissivity |
| $h$ | convective heat transfer coefficient, $W/m^2.K$ | $\sigma$ | Stefan-Boltzmann constant, $W/m^2.K^4$ |
| $k$ | conductive heat transfer coefficient, $W/m.K$ | | **Subscripts** |
| $\dot{m}$ | mass flow rate, $kg/s$ | $A$ | air |
| $Q$ | heat energy, $J$ | $dp$ | dew point |
| $RH$ | relative humidity | $i$ | inlet |
| $t$ | time, $s$ | $g$ | gain |
| $\Delta t$ | time interval, $s$ | $l$ | loss |
| $T$ | temperature, $^oC$ | $o$ | outlet |
| $v$ | wind velocity, $m/s$ | | |

## INTRODUCTION

With rapid rise of energy demand, and subsequently, the growth of environmental issues, many countries have been encouraged to use sustainable and renewable sources of energy [1-4]. Among different forms of renewable resources, solar energy is the most available, viable, and environmental-friendly source of clean energy. Over the past decades,

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engineers and scientists offered and invented numerous useful technologies to harvest solar energy. Asphalt solar collectors (ASCs) are an affordable, sustainable technology that utilizes existing infrastructures to collect solar thermal energy [5]. Asphalt pavements are exposed to solar irradiation for long periods of a day and are heated up to 70 $^oC$ [6, 7]. The ASCs use this available thermal potential by circulating a working fluid through a series of pipes that are embedded in the hot pavement and extract accumulated thermal energy.

In the late 90s, the hydronic ASCs were initially used to keep roads and bridges snow/ice-free during the cold winter days, and a great number of studies dedicated to investigating different aspects of hydronic ASCs [8-12]. Even though nowadays, theses researches have been extended to the other application of ASCs that can be briefly stated as collecting solar thermal energy. The crucial concerns of this class of studies can be summarized in two general categories. One category investigated environmental effects of using ASCs such as reducing the urban heat island effects (UHIEs) [13-15], while the other category analyzed the dynamics of ASCs and evaluated their performance under different design factors such as pipe spacing [16-18]. Mallick et al. [17, 19] studied the concept of extracting heat energy from ASCs by using finite element modeling and testing with numerous samples. Shaopeng et al. [6] experimentally investigated the thermal response of a small-scale ASC to evaluate the effects of flow rate under lab-conditions. A multilayer pavement with a highly porous middle layer was experimentally tested as an active solar collector instead of a conventional ASC with an embedded pipe network to ensure the high performance of this type of solar collector [20]. To overcome hydronic ASC limitations such as water sealing, some studies [7, 21] offered and evaluated a type of air asphalt collector integrated with a chimney. In the other study, Guldentops et al. [16] conducted a research project to develop a modeling framework and validated it with experimental data. The developed model was used to a detailed parametric study of the system and optimized design factors. Pan et al. [22] and Dezfooli et al. [23] presented a literature review that summarized the main achievements of the existing studies and gave some proposals for further investigations on pavement collectors. Predicting the performance of a façade-integrated concrete solar collector was the main scope of O'Hegarty et al. [24] research study. In this research, they experimentally investigated the performance of a façade-integrated collector and validated a 3D numerical model to predict the performance of façade collectors in other climate conditions. In another trial, a 3D CFD model was developed and validated with a laboratory-scale ASC, while the thermal response of the modeled collector was analyzed under different operating conditions such as flow rate and solar irradiance [18]. Sable [25] used a heat transfer augmentation technique (dimple) on the water carrying tube in a constructed concrete solar collector and compared the performance of dimpled tube and smooth tube concrete solar collectors. Other technical features such as glazing strategy and pipes configuration were assessed to improve the thermal performance of ASCs [26, 27]. The other class of investigations is available that focused on the development of 2D or 3D analytical mass and heat transfer models to assess the dynamics of ASCs [28]. Asfour et al. [29] worked on a 2D hydrothermal modeling of porous pavement to predict the temperature field in the pavement structure of hydronic ASCs. Even though new emerging technologies have been risen in recent years and created suitable platforms to harvest energy from asphalt pavements [5, 30], but the ASCs will be in the center of attention for the future decades due to its ease of construction, use, and operation.

The previous literature mainly focused on numerical modeling or experimental investigations under controlled or lab-conditions [16, 18, 20, 25]. Even though these studies offered insightful contributions to our understanding of the dynamics of ASCs, these investigations often used approaches with technical constraints. In most of the performed experimental and numerical analyses, the simulations were performed with the aid of solar simulators with constant irradiation. Furthermore, the variation of environmental conditions such as wind velocity, ambient temperature, and solar intensity was ignored, and these vital parameters were considered fixed and constant during the simulations. The current study represents an experimental analysis of a self-constructed ASC integrated with an ON/OFF switching controller to observe the thermal dynamics and performance of the ASC under the continuous and discontinuous-flow strategies. One of the significant advantages of the present study is to run the tests under field-conditions; hence all the crucial environmental parameters such as solar intensity, ambient air temperature, and wind velocity were measured and monitored over the simulation periods.

In recent years, many techniques and approaches were proposed and evaluated to improve the thermal performance of varieties of solar collectors. The main scope of the present study is to analyze the thermal performance of the constructed ASC by using a timing approach. In this technique, an ON/OFF switching controller runs a circulation pump in specific time intervals, while stagnant water inside the hot pavement has sufficient time to experience higher temperatures, and increases its thermal heat gain. In better words, this paper offers a switching controller and evaluates its performance on system efficiency in an experimental test-bed. To this aim, an experimental set-up was constructed, and the tests were done in several stages with different time intervals to evaluate suggested timing approaches.

## EXPERIMENTAL SET-UP AND EQUIPMENT

### ASC design and construction

The constructed ASC in the present study is composed of a slab of compacted asphalt mixtures. The dimensions of the slab are $0.3m \times 0.4m \times 0.2m$ (Length×Width×Thickness). Table 1 outlines the main characteristics of the constructed ASC. The schematic shape of the designed ASC is shown in Figure 1.

As indicated in Figure 1, the designed ASC includes a wooden framework, a set of 12 $m$ stainless steel pipes, and a slab of asphalt mixtures. The slab contains three layers of compacted asphalt mixtures that were compacted by a hand tamper compactor to minimize the size and number of voids and improve the conductivity of mixtures. It is worth mentioning that the bottom surface of the collector was insulated to eliminate the heat loss due to conduction. During the test, the heat penetrates the asphalt slab via conduction,

**TABLE 1.** The main characteristics of the constructed ASC

| Component of ASC | Specification | | Value |
|---|---|---|---|
| Collector | Collector Dimensions | Length | 3 *m* |
| | | Width | 0.4 *m* |
| | | Thickness | 0.2 *m* |
| | Asphalt Mixture | Bitumen 60/70, crushed sand with a maximum size of 10 *mm* | |
| Tank | Reservoir Tank Capacity | | 100 *L* |
| | Insulation Material | Glass fiber wool | |
| Pipes | Pipe Length | | 12 *m* |
| | Number of Passes | | 2 |
| | Nominal Pipe Diameter | | 15 *mm* |
| | Burial Depth of Pipes | | 3 *cm* |
| | Center to Center Spacing of Pipes | | 110 *mm* |
| | Pipe Material | Stainless Steel | |
| Pump and Fittings | Circulation Pump | Power | 0.5 *HP* |
| | Fitting Connections | Hosepipes | |
| | Insulation Materials | Foamed polystyrene tubes | |

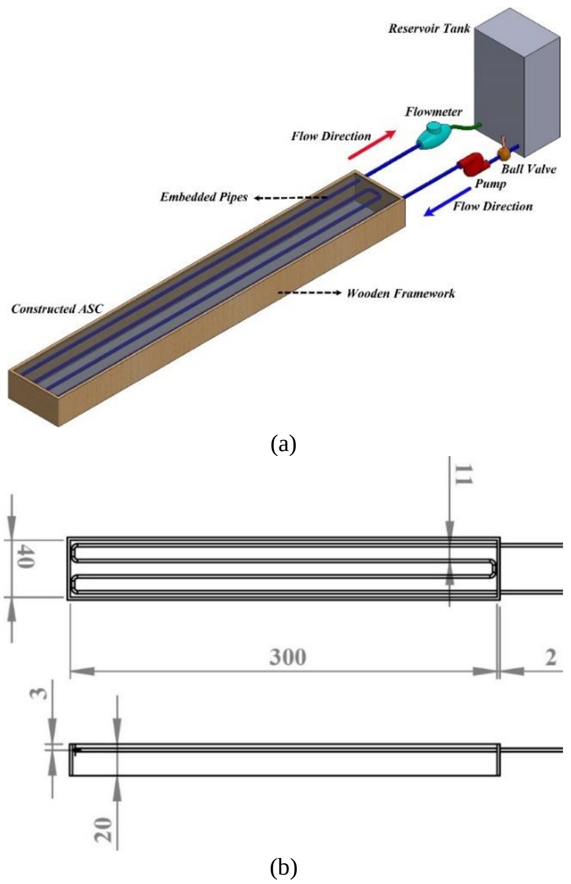



**Figure 1.** (a) The schematic shape of the designed experimental set-up and (b) the asphalt collector dimensions in centimeter

and a temperature gradient is gradually created along with the depth of asphalt layers. Hence, due to the temperature gradient, the pipes' burial depth can play a crucial role in increasing the thermal efficiency of ASCs. The literature review [16, 17] demonstrated the effects of burial depth on the thermal performance of ASCs and gave some comments on the optimum burial depth. With attention to these investigations, the pipe sets were embedded in the middle layer at a depth of 3 *cm*. The pipes were arranged regularly with a center to center spacing of approximately 110 *mm*.

## Energy and exergy analysis of ASC

To evaluate the performance of the constructed ASC and study its thermal dynamics, heat transfer analysis was utilized to obtain cumulative heat gains and heat losses in considered scenarios. Heat losses from the sidewalls and bottom surface of the collector can be ignored, while the top surface is in active interaction with the ambient environment. Equation (1) defines the heat balance at the top surface of the ASC:

$$-k\frac{\partial T}{\partial y} = \alpha_s G + \varepsilon\sigma(T_{sky}^4 - T^4) + h(T_a - T) \tag{1}$$

The Left-hand side of the heat balance equation, Equation (1), presents Fourier's law of heat conduction, where $T$ and $k$ denote the temperature and thermal conductivity of the pavement, respectively. On the right-hand side of Equation (1), $\alpha_s$ is the solar absorption coefficient, and $G$ represents the irradiation. $h$ is the convective heat transfer coefficient, while $T_a$ and $T_{sky}$ are the dry-bulb ambient air and sky temperatures, respectively. Sky temperature is introduced as the hypothetical temperature of the surrounding atmosphere and is calculated by using the Bliss model [31]:

$$T_{sky} = (0.8 + \frac{T_{dp}}{250})^{0.25} \tag{2}$$

Here, $T_{dp}$ is the dew point temperature that can be calculated with high accuracy using the following formula [32]:

$$T_{dp} = \frac{B\left[log(\frac{RH}{100}) + \frac{CT_a}{B+T_a}\right]}{C - log(\frac{RH}{100}) - \frac{CT_a}{B+T_a}} \tag{3}$$

In Equation (3), *RH* defines relative humidity. *B* and *C* are constants and equal to 243.04 and 17.625, respectively. The third term on the right-hand side of Equation (1) represents the convection heat exchange at the top surface. The empirical Bentz model was utilized to calculate the convective heat transfer coefficient, *h*. The Bentz model is based on the wind velocity as an input factor and is given literature [33]:

$$h = \begin{cases} 5.6 + 4v & v \le 5m/s \\ 7.2v^{0.78} & v > 5m/s \end{cases} \tag{4}$$

In Equations (1) to (4), all values of $T_a$, *RH*, and *v* were updated based on the recorded ambient data by the installed weather sensors. The energy analysis provides insight into heat gains and losses during the experimental runs in different scenarios to ease the evaluation of the thermal performance of the constructed ASC. Equation (5) defines the convective-radiative heat loss, $Q_l$ (energy):

$$Q_l = A\Delta t\left[\varepsilon\sigma(T_{sky}^4 - T^4) + h(T_a - T)\right] \tag{5}$$

Here, $A$ and $\Delta t$ are the collector area and time interval, respectively. The first term on the right-hand side of Equation (5) defines the radiative heat loss, while the second term introduces the convective heat loss. The amount of heat gain, $Q_g$, that can be extracted by circulating water through the embedded pipes is given as follows:

$$Q_g = \Delta t\left[\dot{m}c_p(T_o - T_i)\right] \tag{6}$$

In Equation (6), $\dot{m}$ is the mass flow rate of water, and $c_p$ denotes the specific heat capacity of the fluid. $T_o$ and $T_i$ represents the inlet and outlet water temperatures, respectively.

In order to provide further insightful interpretation of the obtained experimental results and precisely judge the performance of the constructed ASC under the continuous and discontinuous-flow strategies, the exergy analysis was performed in the current study. Exergy represents the maximum amount of useful work that can be theoretically produced from the extracted thermal energy and provides an insightful and practical comparison between the different considered scenarios. The useful exergy which is appropriate for low-temperature systems is defined as follows:

$$X_{useful} = \dot{m}_{water}c_{p,water}\left[(T_o - T_i) - T_a\,ln(\frac{T_o}{T_a})\right]\Delta t \tag{7}$$

Here, $X_{th}$ is the useful exergy, while $T_a$ represents the temperature of the ambient environment (in degrees *K*). It appears clear that the closer temperature at the collector outlet into the ambient environment, the lower the value of the useful exergy will be. The actual useful exergy gain considering the water head loss is given as:

$$X_{useful,ac} = X_{th} - E_{pump} \tag{8}$$

where, $E_{pump}$ denotes the amount of consumed energy associated with the circulating pump. The exergy analysis allows independent evaluation of a system regardless of the influence of physical parameters such as collector geometry and configuration.

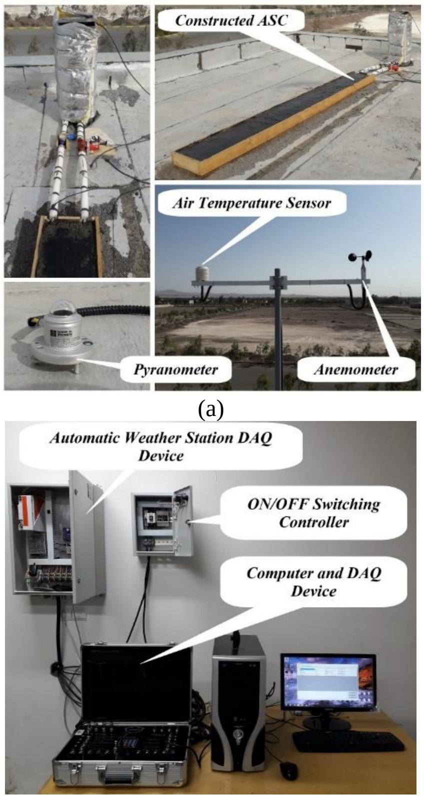
**Experimental system set-up**

Auxiliary components are essential to run the experimental tests and evaluate the dynamics of the constructed ASC under introduced controlling strategies. As shown in the schematic of the experimental system set-up, Figure 2, the other vital component of the designed system comprise circulation pump, flowmeter, reservoir tank, check valve, temperature sensors, pyranometer, anemometer, ON/OFF switching controller, data acquisition (DAQ) device and a computer to run the DAQ software and store the collected data.

Some effective temperatures in the system set-up must be monitored continuously to precisely obtain the system dynamics and performance under the ON/OFF switching controlling strategies. These temperatures include water inlet temperature to ASC (S1), water outlet temperature from ASC (S2), reservoir tank water temperature (S3), asphalt layer temperature at burial depth (S4), asphalt layer temperature at the top surface (S5), and ambient air temperature (S6). Several sensors were used in the system set-up to measure and monitor these temperature variations during the experimental simulation. The used type of water temperature sensors is the negative temperature coefficient (NTC) thermistor, while the solar irradiation and wind velocity were measured by Kipp & Zonen CMP3 pyranometer and NESA VV1C anemometer, respectively.

It is valuable to briefly describe the system procedure or, in other words, clarify the role of each component of the system. The water is circulated through the system by a 0.5 *HP* circulation pump. After circulation, the circulated water is expelled to a 100 *L* reservoir tank. The flow rate of water is measured by a flowmeter that is installed at the outlet of the constructed ASC and, a manual ball valve controls the flow rate of water. A check valve allows water to only flow in one direction to stop the reverse flow of water through pipes. The hosepipes are used to connect the devices, and the foamed polystyrene tubes are employed to insulate water connections and fittings. The reservoir tank is also insulated by glass fiber wool. The installed sensors measure data and send signals to the DAQ device in specific predefined time intervals. The data acquisition device is connected to a host computer that this computer stores and analyses the transmitted signals and converts them to meaningfully measured temperatures.

The main scope of the present study is to investigate the effectiveness of the continuous and discontinuous-flow strategies in the thermal dynamics of the constructed ASC. To achieve this goal, a programmable ON/OFF switching controller was utilized in the system set-up that turns the circulating pump ON and OFF at regular time intervals. The controller was designed such that any different time duration can be selected for the time intervals. This ability can provide this opportunity to study diverse scenarios and expand insight into thermal dynamics. These scenarios include the impacts of the ON/OFF switching controller on the temperature gradient at the inlet and outlet of the collector during the simulation, the thermal efficiency and, the accumulated heat gain and heat loss of the ASC under study.




(b)

**Figure 2.** The experimental set-up component

**Test method**

All the experimental tests to study the dynamics of the constructed ASC were conducted during the springtime, March 1st to June 1st at Renewable Energy Laboratory, Bam, Iran. The experiments were begun at 8:30 A.M. and continued until 5:30 P.M. for approximately 8 hours under the field conditions. After each test, the system was remained in contact with the ambient environment to be in temperature equilibrium with its surroundings. The flow rate of water was kept constant and equal to 25 $L/h$ during the experimental simulation. All of the effective factors, such as environmental factors, were read in every ten seconds to evaluate the dynamics of the set-up. Three different scenarios were considered in the present study to analyze the effectiveness of a simple ON/OFF switching controller in the thermal performance of the system set-up. These scenarios are given in Table 2.

## RESULTS AND DISCUSSION

Ambient factors play a significant role in the dynamics of ASCs. Figures 3a-3c show the measured ambient parameters during the experimental simulation, including solar intensity, $I$ ($w/m^2$), air temperature, $T$ ($^oC$), and wind velocity, $v$ ($m/s$). Each of these factors can influence the performance of the constructed ASCs. The solar intensity gives a sense of the received amount of thermal energy, while the air temperature, in conjunction with the wind velocity, introduce the amount of heat loss due to convection and radiation with the ambient environment. By increasing the velocity of the wind blowing over the collector surface, the convective heat transfer coefficient improves that results in more heat dissipation from the top surface of the collector. Figures 3a-3c represent a high similarity between the magnitudes of the measured ambient factors. The similar ambient conditions provided this chance to perform the experiments in the same operating conditions as the different scenarios were set up. The measured ambient temperature and wind velocity lied between the ranges of 32 $^oC$ to 38 $^oC$ and, 0 $m/s$ to 20 $m/s$ during the simulations, while the solar intensity varied continuously from the minimum value of 700 $W/m^2$, to the maximum value of 1400 $W/m^2$, and vice versa according to the sun's position in the sky.

Figure 4 provides a comparison of temperatures at the burial depth of 3 $cm$ from the top surface of the constructed collector. As shown in Figure 4, the burial layer of pipes experienced higher temperature levels by increasing the power-OFF interval period (The scenarios under study are presented in Table 2). The circulating water extracts and removes thermal energy from the hot asphalt pavement exposed to solar irradiation for hours. By interrupting the circulation of water, the heat accumulates in the asphalt pavement that results in increasing the asphalt temperature.

**TABLE 2.** The considered scenarios with ON/OFF switching controller

| Number of Scenario | Switching ON Interval | Switching OFF Interval |
|---|---|---|
| 1st Scenario | Continuous Running Without Switching ON/OFF | Continuous Running Without Switching ON/OFF |
| 2nd Scenario | 1 *min* | 5 *min* |
| 3rd Scenario | 1 *min* | 10 *min* |

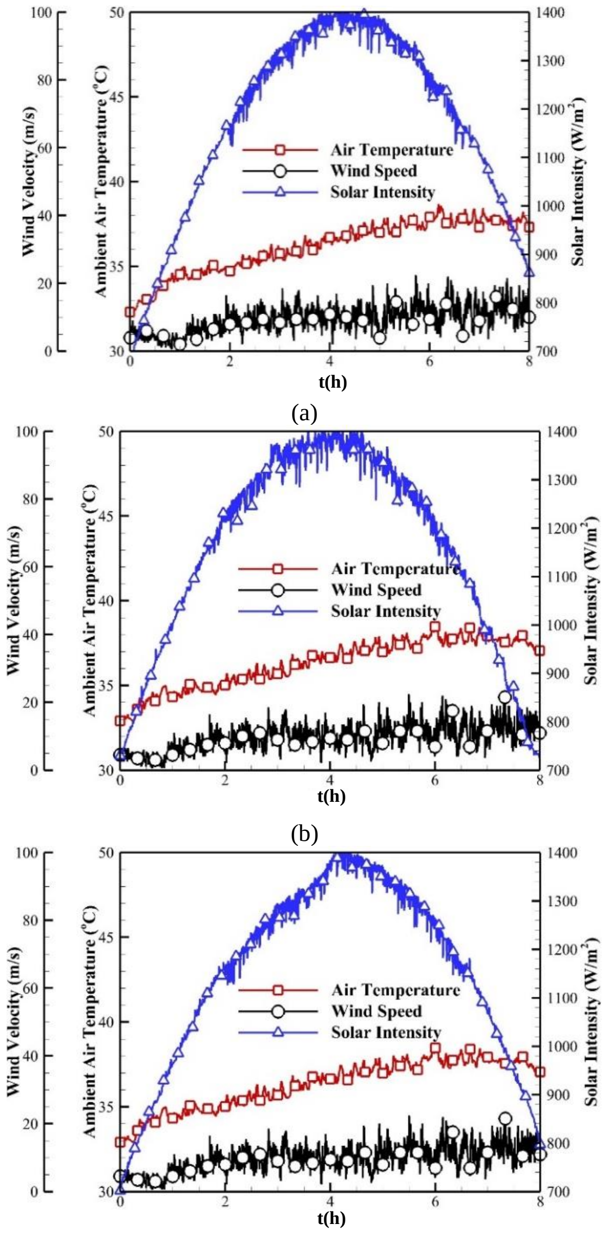



**Figure 3.** The measured environmental factors in (a) 1st scenario, (b) 2nd scenario, (3) 3rd scenario

Figure 5 represents a comparison of temperatures at the top surface of the constructed ASC. The top surface of ASC was continuously in contact with the ambient environment and got influenced significantly by environmental factors such as wind velocity or solar irradiation. As shown in Figures 3a-3c, the environmental factors were changing steadily in time; hence the temperature profile of the top surface under the influence of these continuously varying factors experienced more rapid fluctuations and oscillations during the experimental runs. On the other hand, the temperature profiles at the burial depth show fewer perturbations in comparison with the top layer temperature. In other words, this fact illustrates the effects of varying environmental

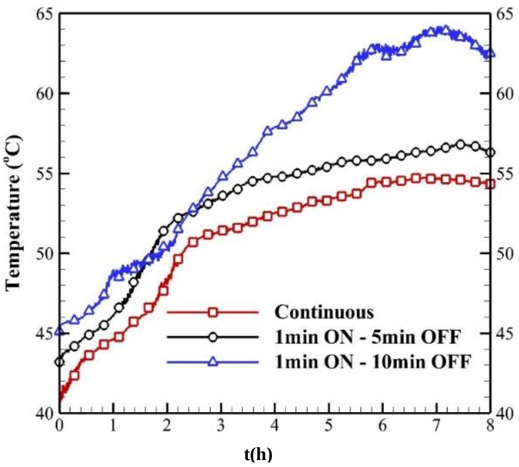



**Figure 4.** The comparison of temperatures at the burial depth of 3 cm

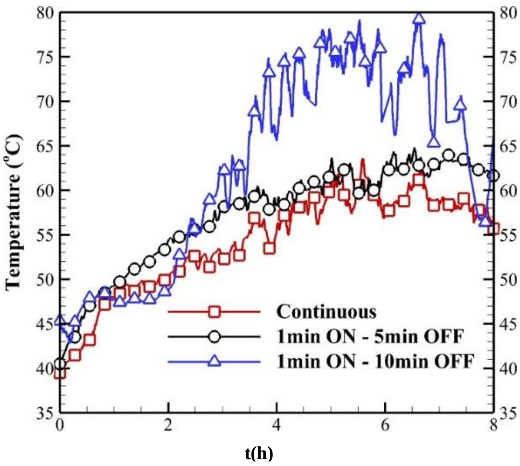



**Figure 5.** The comparison of temperatures at the top surface

factors on the temperature profiles. Also, the temperature of the top surface was affected by the control mode selection of the circulating pump. Extension of the power-OFF interval results in increasing the temperature of the top layer of asphalt pavement. Continuously circulating the water through the embedded pipes causes the accumulated heat to remove steadily, and the asphalt pavement experiences lower temperature, although high-temperature asphalt pavements contribute to rutting distress and asphalt aging. Due to both natural and forced convection heat dissipations, growth of temperature gradient between the top surface of asphalt pavement and the ambient air increases heat loss from the constructed ASC.

Figures 6 and 7 indicate the inlet and outlet temperature profiles of the constructed collector. Using the different control modes to keep the water stagnant in the embedded pipe sets for a higher period, raises the water temperatures in both terminals of the collector, the inlet and outlet terminals. By extending the power-OFF interval from continuous circulation to 10 *min* power-OFF mode, the inlet and outlet temperatures experienced up to 6 $^{o}C$ and 5 $^{o}C$ growth in temperature, respectively. In other words, by extending the power-OFF mode, the circulating water had a sufficiently long time to exchange heat with the hot asphalt pavement; therefore, the constructed ASC can produce a heat reservoir with higher temperatures. Furthermore, it is worth mentioning that the inlet and outlet temperatures in all the considered scenarios approximately reached an asymptote after nearly 5 hours from the starting time in the current experimental study. Due to this fact, the constructed ASC has the capability of heating the circulating water to a specific range, and after reaching an asymptotic temperature, the circulating water did not experience a significant change in its temperature.

One of the crucial signs for the performance evaluation of the constructed ASC is the ability to make a higher temperature difference at the inlet and outlet terminals of the collector. Figure 8 shows the produced temperature gradients between the inlet and outlet of the collector. As shown in Figure 8, the continuous-mode of circulating water can provide a higher temperature difference at the terminals, which illustrates this mode of controlling approach (continuous-flow strategy) gains more heat in comparison with the other ones. Furthermore, it is evident that in the continuous-mode, the greater mass of water was heated during the experimental runs. In better words, in discontinuous-flow strategy, the flowing current was interrupted regularly during the tests. This issue results in a reduction of mass of heated water. By extending the power-

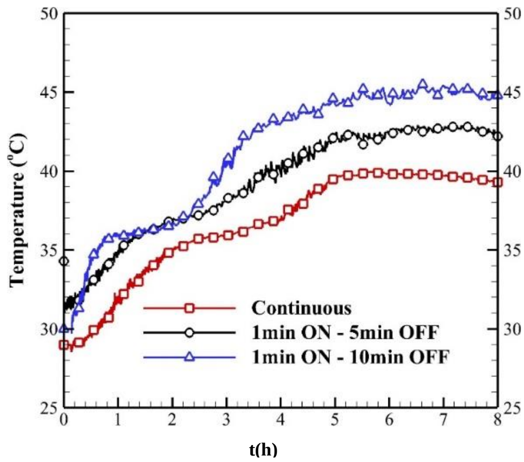



**Figure 6.** The comparison of inlet temperature profiles of the constructed collector

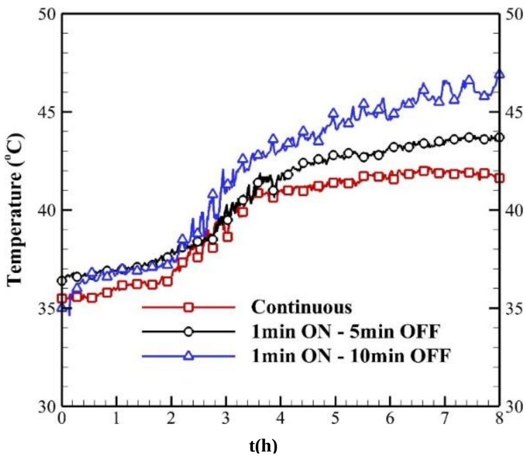



**Figure 7.** The comparison of outlet temperature profiles of the constructed collector

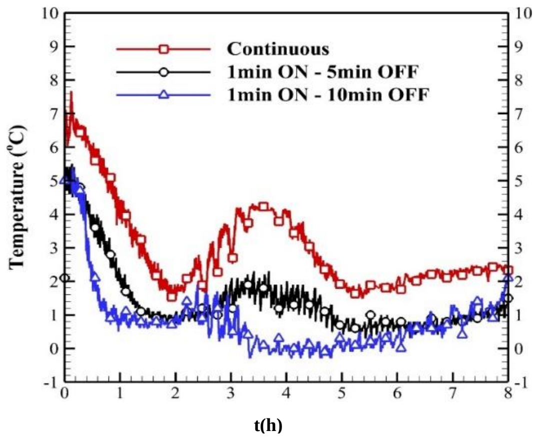



**Figure 8.** The temperature difference between the inlet and outlet terminals of the collector

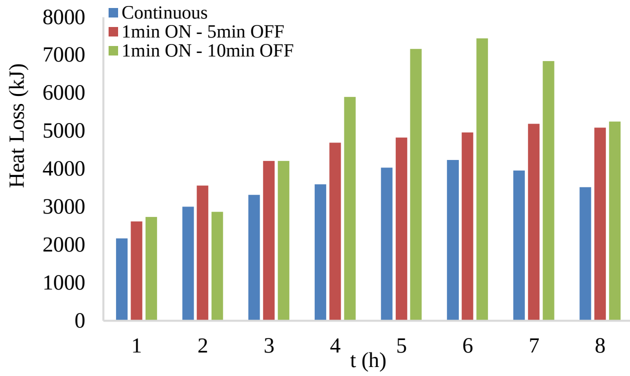



**Figure 10.** The cumulative heat loss from the collector

OFF mode, the temperature difference at the intervals decreases significantly. It can be seen that in the third scenario, the mode of 10 min power-OFF interval, the temperature difference approximately equals zero in some periods of experimental runs that means the heat gain is negligible.

Besides the temperature gradient at the inlet and outlet, a comparison of net cumulative heat gains is another crucial factor in investigating the performance of ASCs. Figure 9 depicts the cumulative heat gain by the collector in the same field and operating conditions. As Figure 9 illustrates, the continuous-mode has more significant potential in accumulating thermal energy in comparison with the other two considered scenarios. The cumulative heat gain was calculated by adding each consecutive heat gain for an hour during the experimental run. It can be concluded that even though by extending the power-OFF mode, the outlet and inlet temperatures increase, but the cumulative heat gain decreases drastically. In other words, the performance and efficiency of a collector are strongly dependent on the heat gain. Therefore, using the ON-OFF controlling approach (discontinuous-flow strategy) to keep the water stagnant in the collector and prolong the heat exchange time reduces the efficiency of the collector that is not a desirable impact. Figure 10 depicts the cumulative heat loss from the top surface of the constructed ASC. As seen in Figure 10, increasing the temperature of the top surface by extending the OFF-mode (as shown in Figure 5) results in a growth in heat loss due to combined convection radiation interaction with the ambient environment.

Figure 11 shows the cumulative exergy during the experimental runs. As shown in Figure 6, the extracted thermal energy with the constructed ASC is available at a low temperature; therefore, it is not remarkably valuable in terms of work (exergy). On the other hand, the energy that was consumed by the circulating pump is significant in comparison with the exergy obtained by the heat source. Since, at the continuous-flow mode, the circulating pump continuously propelled the water; thereby, it consumed a more considerable amount of energy in comparison with the other considered discontinuous-modes. Extension of OFF-mode results in decreasing the consumed energy by the pump; this issue can significantly affect the total cumulative exergy. Total cumulative heat gains, heat losses, and exergies are tabulated in Table 3.

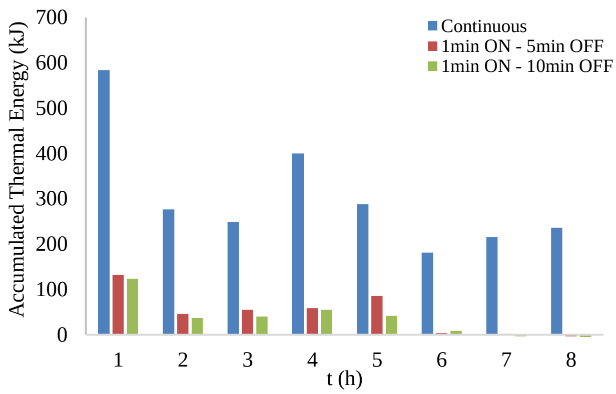



**Figure 9.** The cumulative heat gain by the collector

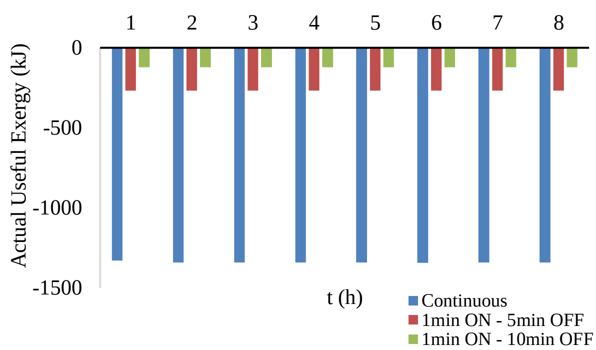



**Figure 11.** The cumulative actual useful exergy

**TABLE 3.** The cumulative heat gains, heat losses and exergies in three different scenarios (kJ)

| | 1st Scenario | 2nd Scenario | 3rd Scenario |
|---|---|---|---|
| Heat gain | 2427.8 | 378.6 | 288.4 |
| Heat loss | 27842.8 | 35164.9 | 42422.5 |
| Exergy | -10726.5 | -2146.6 | -975.0 |

## CONCLUSION

The main subject of the present study is to investigate the effectiveness of employing continuous and discontinuous-flow strategies (ON-OFF control strategy) in the performance of ASCs in field conditions. To this aim, an experimental test-setup was designed and constructed to evaluate the strategies mentioned earlier. Three different scenarios, including continuous-flow mode, 5 *min* power-OFF mode, and 10 *min* power-OFF mode, were considered to assess the performance of a constructed ASC. During the experimental runs, all the critical and effective environmental factors such as ambient air temperature, solar irradiation, and wind velocity were measured, while the ASC operating factors such as the inlet and outlet temperatures were monitored simultaneously. The obtained experimental results illustrate that the discontinuous-flow strategy or, in other words, the ON-OFF control strategy results in increasing the inlet and outlet water temperatures at the collector's terminals, even though the temperature difference significantly decreases that causes the cumulative heat gain reduces. Furthermore, by extending the power-OFF mode, the temperatures of the surface and depth layers grow. Due to these facts, using the discontinuous-flow strategy results in producing water with higher temperatures, even though the cumulative heat gain reduces drastically. To come up with a conclusion, due to the higher temperature gradient between the top surface and the ambient environment, employing the discontinuous-flow strategy increases the heat loss from the collectors that causes the performance of the constructed ASC to reduce. The continuous-flow strategy shows higher performance due to its superior capability in energy accumulation, and inferior heat dissipation. Furthermore, even though the continuous-flow strategy may result in higher performance, the exergy analysis proves that the available exergy reduces significantly due to a large amount of consumed energy by the circulating pump. In better words, pump performance has a remarkable impact on the actual useful exergy of the system.

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**Persian Abstract**

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**چکیده**

کالکتورهای خورشیدی آسفالت (ASC) جایگزینی کم هزینه و قابل اعتماد برای برداشت انرژی از زیرساخت‌های موجود مانند جاده‌ها و مسیرها را با استفاده از تکنیک‌های ساده ارائه می‌دهند. این مقاله یک مطالعه تجربی برای ارزیابی اثربخشی استراتژی‌های جریان مداوم و ناپیوسته در پویایی و عملکرد یک ASC خود ساخته در شرایط میدانی است. برای این منظور، یک کنترل‌کننده سوئیچ خاموش/ روشن دستور می‌دهد تا سیستم را در فواصل زمانی مختلف اجرا و متوقف کند. در طول شبیه‌سازی‌های تجربی، تمام پارامترهای مهم محیطی و عملیاتی اندازه‌گیری و پایش شدند. این رویکرد تأثیر سناریوهای بیشمار با فواصل زمانی مختلف را بر پویایی کالکتور ساخته شده ارزیابی می‌کند. استراتژی‌های جریان مداوم و ناپیوسته با مقایسه سه سناریو مختلف، از جمله حالت جریان مداوم، ۵ دقیقه حالت خاموش و ۱۰ دقیقه حالت خاموش ارزیابی شد. نتایج نشان می‌دهد که با گسترش حالت خاموش، آب برای دوره‌های طولانی‌تر در لوله‌های تعبیه‌شده گرم می‌ماند. بنابراین اختلاف دما در ورودی و خروجی کالکتور کاهش می‌یابد و آب در دمای بالاتر کالکتور را ترک می‌کند؛ با این حال، بهره‌وری ASC کاهش می‌یابد. همچنین اگرچه افزایش حالت خاموش باعث می‌شود که آب گرم‌شده در دمای بالاتر از کالکتور خارج شود، اما به دلیل وقفه مداوم جریان، جرم آب گرم‌شده کاهش می‌یابد. نتایج آزمایش ثابت می‌کند که در استراتژی جریان مداوم، افزایش گرمای تجمعی بهبود می‌یابد. بنابراین، استراتژی جریان مداوم عملکرد بالاتری نسبت به استراتژی جریان ناپیوسته را نشان می‌دهد. تجزیه و تحلیل اگزرژی نشان می‌دهد که با توجه به انرژی مصرفی پمپ، میزان اگزرژی مفید موجود به میزان قابل توجهی تأثیر گذاشته است.