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Enhancement of the Thermal Efficiency of the Evacuated Tubes Solar Water Heater by Adding a Reflector

Baqer A. Alhabeeb*[,1], Thualfaqir J. Kadhim*, Hasan T. Hashim*, and Hayder N. Mohammed*

Abstract – *Evacuated tube solar collector (ETSC) is an efficient means used to harvest direct incident solar energy and convert it into thermal energy. Still always there is a rare area of the tube itself which is not facing the sunshine. Thus, reflectors are used to maximize the collecting area. This study investigated the performance of 21 different configurations of the ETSC system. In this research, three different types of reflective materials were used such as aluminum foil, mirror, and white painting. The aluminum foil was used in five different shapes such as a flat surface, parabolic, V-shape, vertical-zigzag and horizontal-zigzag. While the mirror and white painting were used in a flat shape only. All those types of reflectors were installed at a distance of (0.22, 0.17 or 0.12) m behind ETSC's center. The experiments were conducted during 11th-13th December 2018 under Kerbala, Iraq climate. Each system was compared with a reference one which was set without a reflector. Based on thermal efficiency calculations, the results showed that the flat mirror at a distance of 0.17 m was the best. Also, the orientation of the zigzag surface has a significant effect on efficiency.*

Keywords – *evacuated tube, radiation, reflector, solar thermal, solar water heater.*

1. INTRODUCTION

Using fossil fuels produces harmful emissions which are considered the major cause of global warming. Thus, renewable energy sources should be used to minimize environmental pollution [1]. The sun is the most promising renewable and clean energy source. It emits millions of watts in the form of radiation to the earth. If only a small tiny portion of that energy converted into useful energy, it could be remarkably enough for the whole world people's heat demands [2].

The ETSC technology was proposed for the first time by Emmett [3], and it was considered an effective means of capturing solar energy. The ETSC consists of two concentric tubes separated by a vacuum to prevent heat loss by conduction and convection to the environment. The outer tube is a clear glass transmitting sunlight to the inner tube, which is coated by a selective coating to be the absorber surface. The cylindrical shape of the ETSC maximizes the amount of captured energy daily without a need for a tracking mechanism. The ETSC provides a tremendously high temperature compared to the ambient temperature and works even in extremely cold weather [4].

Commonly, there are three types of ETSCs: liquid-in the evacuated tube, U-type flow inside the evacuated tube and heat pipe evacuated tube [5]. ETSC is used in varied applications such as heating water, conditioning air, generating steam, producing distilled water and cooking [6]. The commercial evacuated tube solar water heater is a liquid-in the evacuated tube. It consists of an array of the ETSC closed at the lower end and attached to an insulated tank at the open upper end. The circulation of water between the ETSCs and the tank is driven naturally by thermosiphon phenomenon. A back-up electric heater usually is used to overcome the intermittency of the sun [7].

Recently, several studies have focused on improving the thermal performance of the evacuated tube solar collector. Two ways could be followed to improve the thermal performance of ETCS such as, modifying either the working fluid or structure. Ferdous *et al.* [8] enhanced the performance of heat pipe-ETSC by using methanol as a working fluid in an air cooling system to reduce the compressor power consuming. Sabiha *et al.* [9] improved the efficiency by using Single-Walled Carbon-Nanotubes nanofluid instated of using just water. Another study done by Iranmanesh *et al.* [10] used graphene nanofluid which also resulted in an enhancement in the thermal efficiency of ETSC. Hussain *et al.* [11] developed the ETSC's thermal performance by using Silver and Zirconium-Oxide nanofluids compared with water. Abd-Elhady *et al.* [12] have increased the thermal efficiency of the ETSC heat pipe when oil and foamed copper were used instead of using air or only oil. Mujawar and Shaikh [13] utilized the Copper-Oxide-Water as a working fluid to rise the thermal performance of ETSC instead of using just pure water. Other studies modified the structure of the ETSC by adding a reflector behind the collector to maximize the amount of harvested incident solar radiation. Thomas *et al.* [14] compared the thermal performance of three configurations of ETSCs: the reference ETSC was set without a reflector, and the other two were set with a flat or parabolic reflective surface. The study found that reflectors enhanced thermal efficiency, especially with the parabolic trough. Nkwetta *et al.* [15] conducted a comparison study between the performance of an aluminum compound parabolic concentrator (CPC) evacuated tube and non-concentrated ETSC. In the research, it was found that the reflector increased thermal efficiency. Also, Kumar *et al.* [16] used a flat

*University of Kerbala, Iraq.

[1]Corresponding author:
Email: baqer.a@uokerbala.edu.iq.

galvanized-iron sheet coated with zinc as a reflective surface to increase the thermal performance of the ETSC used to heat air. Recently, Alkhaledi *et al.* [17] investigated experimentally the thermal performance of seven configurations used mirror-coating reflectors made by 3M Corporation. They used four shapes in their study (*eg.* flat, 60° and 45° V-shape and a half-circle). The first three shapes of the reflectors were set at distance (*eg.* 0.15 and 0.10) m behind the ETSC's center while the half circle reflector set only at a specific distance in which the ETSC was placed at focal axis. The study reported that all kind of the reflectors provided an enhancement in thermal efficiency, and the best one was 60°V-shape at a distance of 0.15 m. Bisla and Mor [18] studied the effect of parabolic and flat reflectors on the thermal efficiency of ETSC, and they found that both cases were better than ETSC without any reflector. The tracking system of CPC was investigated by Wang *et al.* [19] and showed improving double times in the optical efficiency than non-tracking system.

This study is investigating the thermal enhancement of the evacuated tube solar collector by examining 21 different configurations. It is introducing for the first time, according to the authors' literature, a new shape of a reflector which is zigzag shape made from aluminum foil to be compared with common ones. Also, this study investigated experimentally three distances at which a reflector installed behind ETSC rather than just one or two as it mentioned in the literature. The current research could be highly contributed to find out the best configuration of a reflective surface integrated with commercial evacuated tube solar water heater to increase its thermal performance and reduce energy consumption. Also, the current study is introducing experimental raw data under Kerbala climate conditions.

2. METHODOLOGY

2.1 Rig Setup

To find out the effect of different types of reflective materials and configurations on the thermal performance of a concentrated water-in-glass evacuated tube solar collector, the rig shown in Figure 1 was constructed. Eight of identical commercial ETSCs with inner, outer diameter and length of 0.047 m, 0.059 m, and 1.75 m, respectively were installed on an iron farm with a tilt angle of 42°. The inclined angle of 42° was chosen according to a previous local study done by Al-Mashat and Hasan [20] taken place under Baghdad's climate conditions. Also, the tubes were separated at a distance of 0.25 m from center to center to minimize the effect of each other system. One of the ETSCs was set without a reflector to be a reference system. Three types of reflective materials (*eg.* aluminum foil, mirror, and white painting) and four shapes (*eg.* flat, parabola, 120°V-shape and zigzag) were used. All reflectors were fixed on a movable wooden background installed behind the tubes to change the distance (d) of the reflector form the tube's center to a desired one (*eg.* 0.22, 0.17 or 0.12) m. Three flat reflectors were constructed from the three different materials mentioned above. The other four reflectors shown clearly in Figure 2 were constructed by using the aluminum foil only. Machined iron sheets were used to create the shapes of the parabola and 120°V-shape reflectors. The rest two zigzag reflected surfaces were shaped by hand and attached on the wooden background directly.

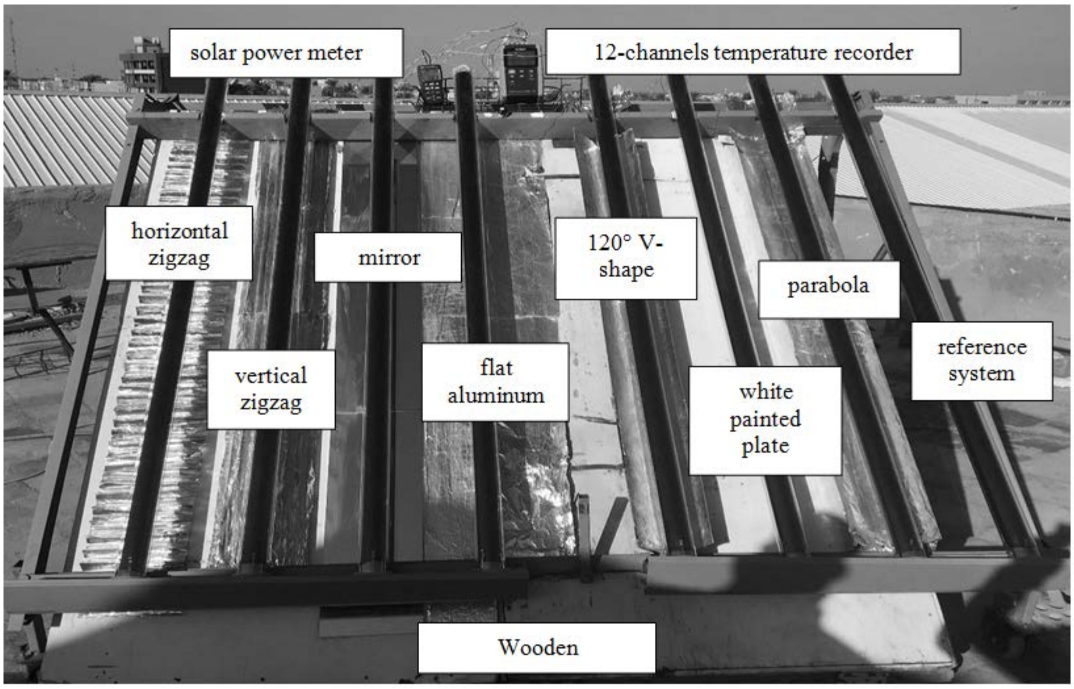
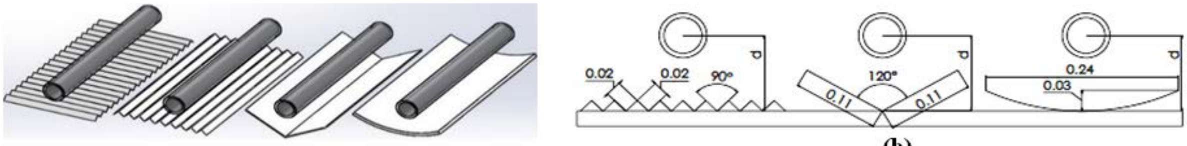


Fig. 1. Rig setup.



(a) (b)

Fig. 2. (a) Arrangement of the reflectors with respect to ETSC, (b) Details of the zigzag, 120° V-Shape and the parabola trough dimensions.

(a) (b)

Fig. 3. (a) Photograph of BTM-4208SD data logger, (b) Photograph of solar power meter.

Table 1. Details of considered tests conducted in this study.

Date (dd/mm/yy)	time	d (m)	I_{avg} (W/m^2)
11/12/18	10:30 -14:00	0.22	915.55
12/12/18	10:30 -14:40	0.17	785.88
13/12/18	10:30 -14:20	0.12 (at the focal point for parabolic trough)	867.73

2.2 Measuring Devices

In the current experiments, two measuring devices were used. Data logger (BTM-4208SD) 12-channels temperature recorder shown in Figure 3a was used to record measured temperatures on SD-Ram in separate Excel sheet. Its accuracy is ± (0.4 % + 0.5 ℃) [21] which means ±(0.004*measured value + 0.5 ℃). The other device was a solar power meter model: TES-132 shown in Figure 3b with an accuracy of ± 10 W/m^2 [22]. It was used to measure and record solar intensity at each set period time.

2.3 Experimental Procedure

After installing eight ETSCs on the frame, the movable wooden background with reflectors was set at a distance (d) of 0.22 m behind the ETSCs. Each ETSC filled with 3kg water and a probe of K-type thermocouple was inserted in each tube at the middle. Another probe was used to measure the ambient temperature. All probes were connected to the data logger (BTM-4208SD) 12-channels temperature recorder to measure and record water temperature every five minutes. Timely, the solar power meter was set to measure and record solar intensity every five minutes also. All recordings were started at 10:30 am and finished when water reached boiling state for each system. The same procedure mentioned above was repeated but at a distance (d) of (0.17 and 0.12) m. Also, the one set of experiments (three consecutive days) were repeated three times during October, November and December, but the thermal behavior was almost the same. Thus, the current study used the data obtained during December as detailed in Table 1.

2.4 Parameters

Two parameters were chosen in this study, such as initial water temperature (T_i) and final water temperature (T_f). For a comparison purpose, the boiling temperature of water (100 ℃) was chosen to be the comparative parameter. Based on that, the period time for each system reaching the boiling condition was determined. The instantaneous thermal efficiency (η) for each system was calculated by Equation 3 [15]-[16], [18] with time term modification.

$$q_{out} = m\, C_p\, (T_f - T_i) \tag{1}$$

$$q_{in} = I_{avg} * A * t \tag{2}$$

$$\eta = \frac{q_{out}}{q_{in}} \tag{3}$$

where q_{out} is the heat gained by water (J), q_{in} solar heat (J), m water mass (kg), A absorbance area (m^2), C_p water specific heat = 4185.5 J/kg ℃, T_i initial water temperature ≈ 20 ℃ and T_f final water temperature ≈ 100 ℃, I_{avg} average solar intensity (W/m^2) and t the period time to reach the water boiling temperature *(sec).*

3. RESULTS AND DISCUSSION

All measurements were taken three times. In other words, all experiments were conducted in nine days. It was observed that all systems behaved almost the same under varied solar intensity. Thus, for the simplicity, the experimental data obtained on 11th, 12th and 13th December 2018 under Kerbala's climate conditions was considered. The analyses of the reference system (without a reflector) and other systems were done base on the required time to reach the boiling temperature of the water inside the ETSC. The three tests were done during three consecutive sunny days with a little difference in the solar intensity as seen in Figure 4. The figure includes upper three curves representing solar intensity, while the lower three curves representing the ambient temperature.

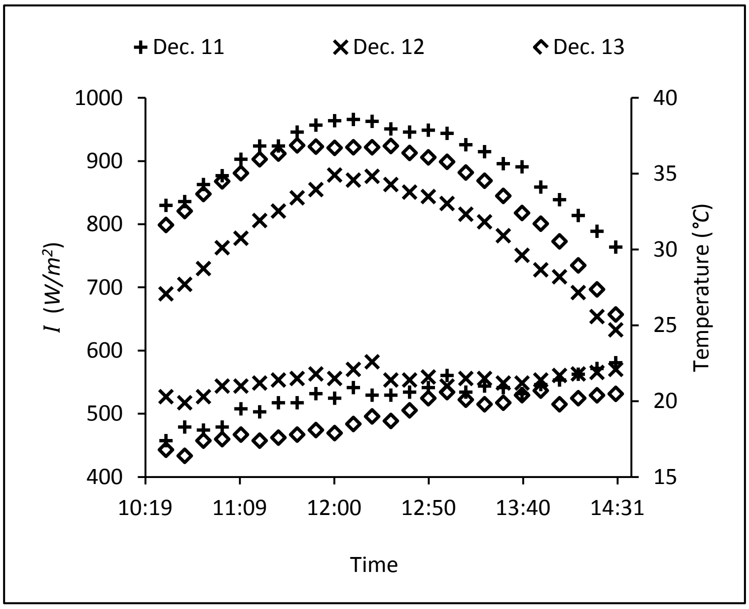


Fig. 4. The solar intensity and ambient temperature during the experiments period.

Table 2 shows the comparisons between the reference ETSC system and the other ETSCs installed in front of reflected surfaces in terms of time reduction to reach the water boiling temperature, and the increasing in the thermal efficiency. The percentage of time reduction (t_{red}) and increasing in gained heat (q_{inc}) and thermal efficiency (η_{inc}) were calculated by Equations 4, 5, and 6, respectively.

$$t_{red} = \frac{t_{ref} - t_{sys}}{t_{ref}} * 100\% \quad (4)$$

$$q_{inc} = \frac{q_{sys} - q_{ref}}{q_{ref}} * 100\% \quad (5)$$

$$\eta_{inc} = \frac{\eta_{sys} - \eta_{ref}}{\eta_{ref}} * 100\% \quad (6)$$

Where ref refers to the reference system (without a reflector) and sys refers to the other configuration systems (with a reflector).

From Table 2, it is noticed that all kind of reflectors led to reducing the required time to reach the water boiling temperature compared with the reference side. In particular, the flat mirror set at 0.17 m and V-shape set at 0.12 m provided a significant reduction in the required time when it is compared with ETSC set with a reflector. They reduced the time by 36% and 37%, respectively. Flat shapes provided the best reduction in time when they were set a distance of 0.17 m even the average solar intensity was the lowest. Meanwhile, the parabolic shape gave the best time reduction when ETSC was set at its focal axis. Also, it is quite noticeable form the table the horizontal orientation of the zigzag shape increased the harvested amount of solar heat better than the performance of the vertical orientation. Generally, It was found that all kinds of the reflectors used in this study increased the thermal efficiency of ETSC, and this finding was in consistence with the findings from [14]-[18]. Also, Figure 5 visualizes clearly compassions between the integrated ETSC with a reflector themselves and with the reference ETSC, which was set without a reflector.

3.1 Uncertainty (U)

The propagation of error in determined values of the thermal efficiencies in this study was calculated according to Kline and McClintock [23] method. Significant errors came from the uncertainty of the measuring instruments. Thus, the uncertainty of a determined efficiency (U_η) was obtained as follow:

According to Equation 3, let the thermal efficiency (η) be a function of independent variables:

$$\eta = f(T_f, T_i, I_{avg}) \quad (7)$$

For small variations in the variables, Equation 7 can be expressed linearly

$$\sigma\eta = \frac{\partial \eta}{\partial T_f}\sigma T_f + \frac{\partial \eta}{\partial T_i}\sigma T_i + \frac{\partial \eta}{\partial I_{avg}}\sigma I_{avg} \quad (8)$$

Finally, the U_η is calculated by taking the stander deviation of Equation 9.

$$U_\eta = [(\frac{\partial \eta}{\partial T_f}\sigma T_f)^2 + (\frac{\partial \eta}{\partial T_i}\sigma T_i)^2 + (\frac{\partial \eta}{\partial I_{avg}}\sigma I_{avg})^2]^{1/2} \quad (9)$$

Where: $\sigma I_{avg} = \pm 10\ W/m^2$, $\sigma T_f = \pm 0.9$ ℃ and $\sigma T_i = \pm 0.58$ ℃.

By using Equation 9, the uncertainties in all calculated efficiencies values represented in Figure 5 were in the range between $\pm$(0.2467 to 0.3915), and they were not represented in error bars in the figure due to their small values.

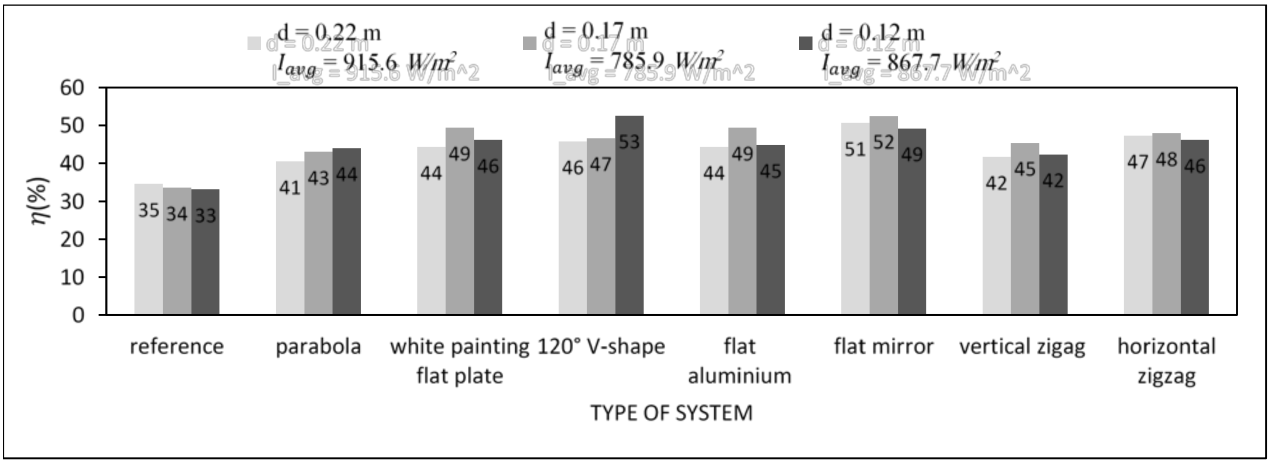


Fig. 5. The thermal efficiency of modified systems compared with the reference system.

Table 2. Shortening time and increasing thermal efficiency percentages with respect to reference system.

Reflective Material	Shape	*d (m)*	I_{avg} *(W/m²)*	t_{red}(%)	η_{inc} (%)
mirror	flat	0.22	915.55	32	46
		0.17	785.88	36	56
		0.12	867.73	33	48
aluminum foil	flat	0.22	915.55	22	28
		0.17	785.88	32	47
		0.12	867.73	26	35
	parabola	0.22	915.55	15	17
		0.17	785.88	22	28
		0.12	867.73	25	34
	120° V-shape	0.22	915.55	24	32
		0.17	785.88	28	39
		0.12	867.73	37	56
	vertical zigzag	0.22	915.55	17	21
		0.17	785.88	26	35
		0.12	867.73	22	28
	horizontal zigzag	0.22	915.55	27	37
		0.17	785.88	30	43
		0.12	867.73	28	39
white painting	flat	0.22	915.55	22	28
		0.17	785.88	32	47
		0.12	867.73	28	39

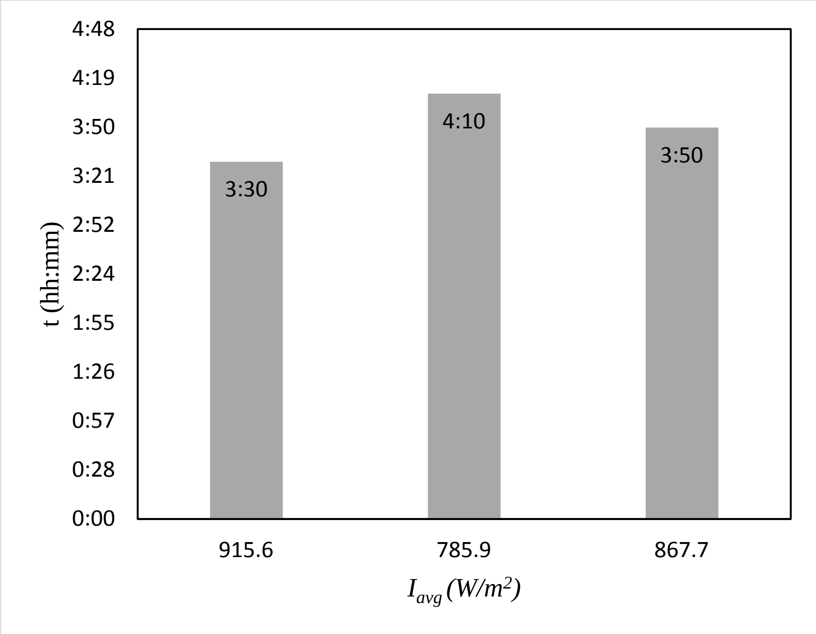


Fig. 6. The required time to reach the water boiling temperature at each day for the reference system.

3.2 *Effect of Parameters*

3.2.1 Solar intensity (I)

It is very obvious that the solar intensity has a major effect on the ETSC since it is the source of heat. As it is seen in the Figure 6 for the reference system set with no reflector, the system required more than 4 hours to reach the water boiling temperature when the average solar intensity was 785.9 W/m^2. While it required less than that time when the average solar intensity was (915.6 and 867.7) W/m^2. This finding is in agreement with what Alhamid *et al.* [24] reported in their study.

3.2.2 Distance (d)

Figure 7 clearly shows the critical range distance of the reflector behind ETSC for flat and zigzag surfaces. In other words, all these systems provided the highest thermal efficiency at a distance of d = 0.17 m even the solar intensity was the lowest compared to those at the other distances as explicit in the Table 1. The scenario is entirely different at the parabola and 120°V-shape. They both provided the best performance at a distance of 0.12 m. In This study, a distance of 0.12 m was the parabolic trough focal point, and its result was in consistence with the report presented in [25].

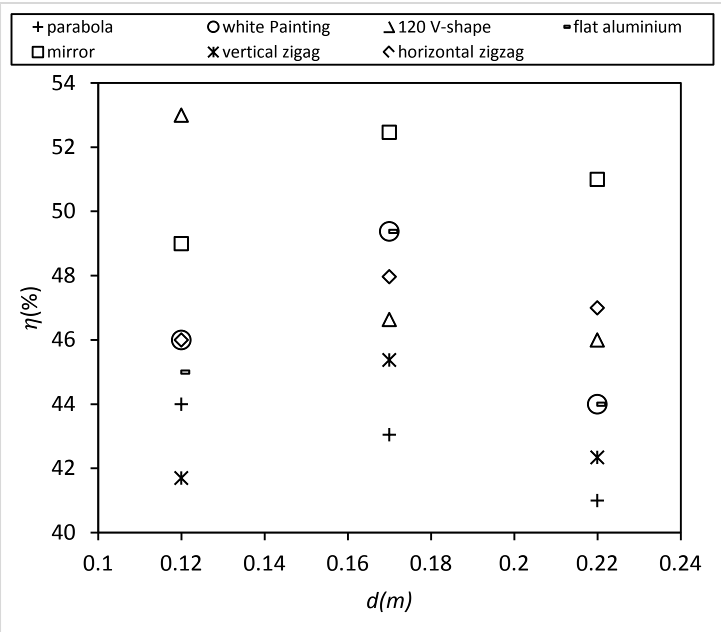


Fig. 7. The instantaneous thermal efficiency as a function of the distance between the reflector and ETSC's center.

Table 3. The heat gain enhancement according to the distance between the ETSC's center and the reflective flat and V-shaped surface behind it.

	Shape of Reflector	*d* (m)	q_{Inc} (%)	I_{avg} (W/m^2)
Current Study	flat mirror	0.12	48	867.7
		0.17	56	785.9
	flat aluminum	0.12	35	867.7
		0.17	47	785.9
	flat white painted plate	0.12	39	867.7
		0.17	47	785.9
	120°V-shape	0.12	59	867.7
		0.17	39	785.9
Alkhaledi *et al.* [17]	flat reflective background	0.10	80	….
		0.15	83	….
	45°V-shape	0.10	150	….
		0.15	137	….
	60°V-shape	0.10	73	….
		0.15	161	….

Table 3 shows the agreement and contrast with findings in reference [17] regarding flat and V-shaped reflectors at close and apart from ETSC. The current study agreed with reference [17] that a flat reflector increased the heat gained further when it was installed at apart distance of (*eg.* 0.15 or 0.17) m rather than the close distance of (*eg.* 0.1 or 0.12) m. For example, in the current study, the flat aluminum increased the gained heat by (35 and 47) % compared with the reference system when it was installed at (0.12 and 0.17) m, respectively. The same thing was reported by reference [17] in which a flat reflector increased the heat gained by 83% when it was installed at 0.15 m and 80 % at 0.1 m. On the other hand, [17] reported that (45° and 60°) V-shaped reflector behaved differently. For instance, 45°V-shaped provided a better increase in the gained heat when it was set at a distance of 0.1 m rather than at 0.15 m while 60°V-shape behaved the opposite. In the current study, 120°V-shape is similar to 60°V-shape used in reference [17], but it performed differently as it is explicit in the Table 3. A V-shape surface reflects radiations from both sides to intersect at specific points. Thus, appearing similarity and difference regarding the V-shapes between the current study and [17] could be due to the varying position of the intersecting points.

3.2.3 Reflective material

In the current study, three different types of reflective materials (*eg.* aluminum foil, white paint and mirror) were used. For comparison purpose, three flat surfaces were made from those materials and treated identically during experiments. Figure 8 shows clearly that the mirror was better than both aluminum and white paint for all distances by providing higher thermal efficiency. Mirror provided the best performance due to its high reflectivity [26]. While the reflective properties of aluminum and white paint performed almost the same especially at distance (0.17 and 0.022) m.

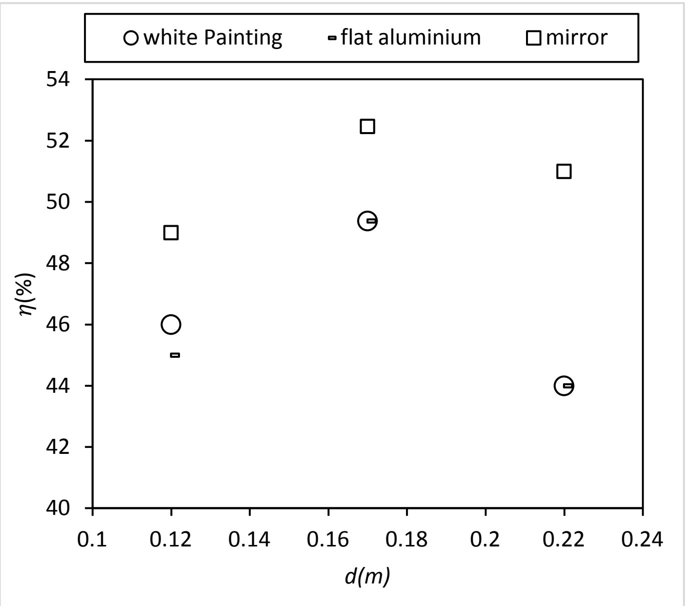


Fig. 8. The reflective martial effect on thermal efficiency.

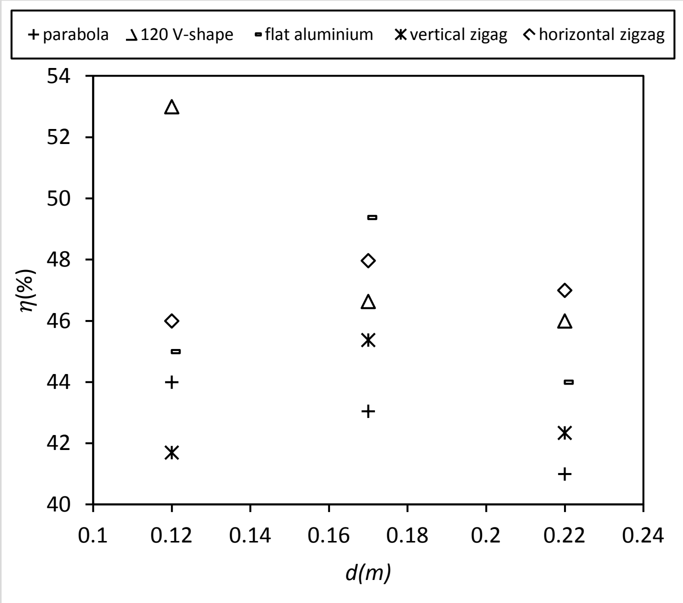


Fig. 9. The configuration effect of reflectors on thermal efficiency.

3.2.4 Configuration

The shape effect of reflectors which were made from the same material has addressed in this study. Aluminum foil sheet was used to create four different reflective shapes (*eg.* V-shape, parabola, flat and zigzag). Figure 9 shows a comparison between those reflectors. At a distance 0.12 m, the V-shape provided the highest thermal efficiency of 53% compared with the others. However, flat surface aluminum reflector dominated on others when they were set at distance of 0.17 m. Whereas, at a distance 0.22 m the horizontal zigzag overcame on the other types of shapes by providing thermal efficiency of 47%, and V-shape came in second place at 46%.

3.2.5 Orientation effect

In the current study and for the first time, the zigzag shape was used and investigated as a reflective surface for ETSC. The results showed that the orientation of this shape concerning ETSC's axial direction significantly affected the thermal performance. Figure 10 shows that the horizontal orientation of the zigzag shape provided better thermal efficiency than the vertical one for all installing distances. The difference was high at distances of (0.12 and 0.22) m while it was reduced at a distance of 0.17 m.

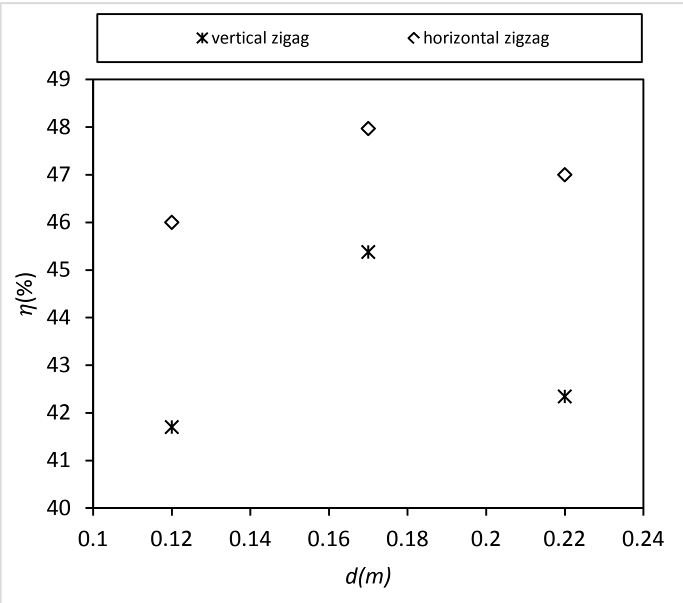


Fig. 10. The zigzag orientation effect on thermal efficiency.

4. CONCLUSION

This study successfully investigated the enhancement of the thermal efficiency of ETSC by adding a reflective surface behind it. The investigation included using three different types of reflective materials, four different shapes and three installation distances. Three experiments were done according to the number of installing distances in three consecutive sunny days during December 2018 under Kerbala climate conditions. Conclusions of the study are explained as follow:

1. All configurations of the reflectors which were integrated with ETSCs maximized the harvested solar heat as compared with the ETSC set without a reflector.
2. Mirror has better reflective characteristics compared with white painting and aluminum foil.
3. Flat and zigzag surfaces provided better reflected solar radiation when they were installed at a distance of 0.17 m rather than at (0.12 or 0.22) m. However, parabolic trough and 120°V-shape surfaces performed better at distance of 0.12 m.
4. Horizontal orientation zigzag with respect to the axial direction of ETSC performed better than the vertical case.
5. The best reflected configuration was the flat mirror at a distance of 0.17 m if the amount of the solar intensity is considered.

Improving the thermal efficiency of evacuated tube solar collector helps to use solar energy efficiently and leads to reduce using fossil fuel.

NOMENCLATURE

$ETSC$	evacuated tube solar collector
d	distance between the ETSC's center and the background [m]
I	solar intensity [W/m^2]
q	heat [kJ]
T	temperature [℃]
m	water mass [kg]
A	absorbance area [m^2]
t	time [sec]
η	thermal efficiency
avg	average
i	initial
f	final
out	output
in	input
ref	reference
sys	system
red	reduction
inc	increasing
U	uncertainty
σ	variation

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