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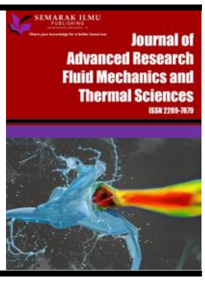

The Effect of Using Secondary Reflectors on the Thermal Performance of Solar Collectors with Evacuated Tubes

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ABSTRACT

The aim of this paper is to improve the thermal performance of the evacuated tube solar collectors by using secondary reflectors and covering the collector surface area with an aluminum foil. Adding a secondary reflecting surface in the form of a parabola fixed on the end of the parabolic trough, acts as an additional reflective surface, which increases the input energy to the solar collector and consequently improves the thermal output of the collector. Two solar collectors were manufactured, one with modifications and the other without modifications, which is taken as a reference for the sake of comparison. Four experiments were performed; the first and second experiments reported the influence of adding a horizontal and a vertical secondary reflector on the solar collector efficiency. In the third and fourth experiment the effect of covering the collector surface area with aluminum foil together with a secondary vertical reflector on the heat gained by the bulb is examined. It is found that the average temperature of the heat pipe bulb in case of a secondary reflector installed horizontally is about 2.5% greater than the average temperature of the reference collector, while in case of the secondary reflector installed vertically is 7% greater than the reference collector. Adding the secondary reflecting surface in the vertical position, and covering the surface area of main parabola and the secondary reflector with aluminum foil, has increased the temperature of the heat pipe bulb by 11%. Finally, adding a secondary vertical reflector to the parabolic trough collector and covering both reflectors, i.e. the primary and the secondary reflectors, with aluminum foil improve the heating capability of the solar collector.

1. Introduction

Energy with its various sources plays an important and essential role in enabling countries to progress and advance, also it contributes to the human well-being. The demand for different energy sources, especially traditional ones such as fossil fuels has increased, leading to the reduction of them. In addition to the damaging effects that resulted from the use of fossil fuels, such as environmental pollution, serious thinking has begun in alternative energy sources. Perhaps the most

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important area that scientists have touched in recent decades is renewable energy. The most important energy of renewable energies is solar energy, because it is abundant and limitless, also, it can be transferred to other types of energy, such as thermal, electrical, and mechanical. Research and experiments have focused on developing means of utilizing them and finding scientific solutions to the most important problems facing their use to cover the human need, and to limit the reduction of traditional energy sources. Sunlight is a renewable energy that can be efficiently used for energy generation and saving electric lighting and electrical energy consumption in buildings, which is increasing due to population increase [1].

Much research has focused on developing and improving the Concentrated Solar Power (CSP) plants, because these technologies are capable of producing large quantities of electricity, especially in rural areas with reasonable installation costs. The Parabolic Trough Collector (PTC) is the most mature and cost-effective technology, and is one of the most promising technologies used to convert solar radiation into a beneficial thermal process [2]. PTC is used to concentrate the high solar flux on a small area of the evacuated tube in order to obtain a higher fluid temperature [3]. However, the thermal efficiency of PTC is one of the research issues that have always been a matter of great importance. Numerous studies [4] have been made on metallic reflective surfaces to reach a high degree of reflectivity. It is found that silver mirrors are less durable than aluminum mirrors, although, it showed better reflectance and consequently resulted in higher efficiency. Despite of the many studies that have been done on reflective surfaces, it is clear that more work remains to be done in the future in order to achieve high reflections at low costs [5].

1.1 Effect of Secondary Reflectors on the Efficiency of Evacuated Tube Solar Collectors

The primary reflective surface is a surface that reflects the incident solar radiation to the receiver. The interception of the radiation flow by the receiver depends on factors such as the edge angle of the solar collector, errors of the reflecting surface, the accuracy of the tracking mechanism, the rigidity of the structure to withstand wind, and self-loading. The strong solar radiation scattered around the receiver leads to a great visual loss and hence thermal loss. A lot of work has been done to reduce radiation scattering, such as the use of aplanatic mirrors [6], also, the use of a secondary reflector can improve the performance of a PTC. Shneishil [7], Qiang *et al.,* [8], Collares-Pereira *et al.,* [9] and many other researchers reported that the secondary reflector are important for increasing heat gain by solar collectors. They proposed a new two-stage optical design for parabolic trough solar collectors with tubular absorbers, such that the concentration ratio can increase by a factor of 2.5 relative to the conventional design. The second stage involves asymmetric non imaging concentrators of the compound parabolic collector, facing segments of the parabolic first stage. Roberto *et al.,* [10] designed a secondary reflector at the end of the combined basin in order to enhance visual performance. It was decided that visual improvement is 12.6% for θ=15°, 29.8% for θ=30° and 59.16% for θ=45°. Spirkl *et al.,* [11] studied the effect of a flat secondary reflector, and reported that the secondary reflector increased the concentration of solar radiation by 77% of the theoretical maximum distribution of solar energy and the transmission efficiency was 90%. Bharti *et al.,* [12] examined a Parabolic Secondary Reflector (PSR) as well as a Triangular Secondary Reflector (TSR), and compared the results with a PTC without a Secondary Reflector (WSR). It has been found that a maximum thermal efficiency of 24.3%, 22.5% and 17.8% is observed in the case of PSR, TSR and WSR conditions, respectively. Bhowmik and Amin [13] improved the efficiency of a flat solar collector by using flat reflectors at the sides of the collector. It became clear that the overall efficiency of the collector increased by 10%, when using a reflector with the collector. Rodriguez-Sanchez and Rosengarten [14] examined the influence of adding a flat secondary reflector over the evacuated tube of PTC, and it was observed an increase in the concentration percentage of 80%, whereas the shade area in the primary reflector is less than 15%. Weldu *et al.,* [15] examined the influence of reflector solar tracking on the performance of a solar box cooker, and it is concluded that it possible to reduce the cooking time by 19% due to the reflector solar tracking compared to a fixed reflector. Zhu [16] developed an innovative optimization method to optimize the secondary-reflector profile of a generic linear Fresnel collector, and such a method can be applied to other types of solar collectors. De la Mora *et al.,* [17] studied the feasibility of using a secondary reflector made of porous silicon. It was observed that a major deterioration in the secondary reflective surface is due to the heat, so a cooling system was introduced to the secondary reflective surface to preserve the reflector performance. This study also opened the possibility of building multiple mirrors direction with the ability to fully reflect radiation in a given range for all possible incidence angles. Gong *et al.,* [18] used an innovative design method for the Secondary Reflector (SR) based on an adaptive approach, such the SR is step wise optimized to reflect back part of the solar radiation that has been reflected by the primary reflector and not captured by the receiver, and it has been shown that the optical efficiency of solar collector could be increased by 5.2% and thermal efficiency by 4.9% based on the proposed approach. Bellos *et al.,* [19] optimized the geometry of the secondary reflector of a linear Fresnel systems using Bezier polynomial parameterization, and it is found that an optical efficiency of 72.84% and a thermal improvement of 20.50% were reached based on the optimized design of the secondary reflecting surface.

1.2 Effect of the Aluminum Foil on the Efficiency of Evacuated Tube Solar Collectors

Andemeskel *et al.,* [20] studied the effect of the aluminum fin thickness inside evacuated tubes, and experiments were conducted for three different thicknesses, i.e. 11 µm, 13 µm and 24 µm. The results proved that there is an increase in the heat removal factor and the thermal efficiency of the collector when using a fin with a thickness of 11 µm. Mahallawy *et al.,* [21] conducted a study aiming to determine the best metallic reflector for parabolic solar collectors used in water desalination units. These materials were aluminum foil with a thickness of 6 µm, 86 µm, and aluminum sheets of 1 mm thickness, and it is noted that the surface with the lowest roughness, i.e. the lowest thickness, has the best surface reflectivity and leads to the highest desalination rate. Sagade *et al.,* [22] studied a prototype of a parabolic solar collector made of mild steel and its surface covered with aluminum foil with a thickness of 10 microns as a selective surface. The performance of the solar collector was evaluated and the study showed an immediate efficiency of 60% with the top cover. Pozzobon *et al.,* [23] showed that the aluminum foil has the same overall reflectivity, about 86% in the visible range and 97% in the radiation. Ahmed *et al.,* [24] investigated the influence of the reflective surface material of parabolic solar cookers. They designed three stoves with different reflective surfaces, the first is stainless steel, the second is aluminum foil and the third is Mylar tape. It is found that the Mylar tape is the best reflective surface, then aluminum foil, finally stainless steel. The temperature gain for water when using a reflective surface of stainless steel, aluminum foil and Mylar tape are 58.2°C, 74.5°C, and 74.5°C, respectively.

The objective of this research is to examine the influence of covering the collector surface area of the PTC with an aluminum foil, as well as adding a secondary reflector to the collector. The purpose of a secondary reflective surface in the form of a parabola is to enhance the optical and the thermal performance of the PTC as a result of collecting solar rays from other directions and focusing them on the main reflecting surface. Two solar collectors were manufactured, one with modifications and the other without modifications, which is taken as a reference for the sake of comparison. Four experiments were performed, in first and second experiments the influence of adding a horizontal and a vertical secondary parabola, i.e. a secondary reflector, on the output of the solar collector are examined, respectively. In the third and fourth experiment the influence of covering the collector surface area with an aluminum foil together with a secondary vertical parabola is examined.

2. Experimental Procedure

2.1 Experimental Setup

Two identical units of the Parabolic Trough Solar Collector (PTSC) with evacuated tube were manufactured, one is taken as a reference, and the other is the one where modifications are applied, as shown in Figure 1. The reference collector is manufactured for the sake of comparison with the modified collector. The dimensions of the PTSC are given in Table 1. The reflecting surface of the PTSC is polished aluminum. The temperature of the bulb of the heat pipe is measured every ten minutes, as well as the solar irradiance. Both the thermocouple and the heat pipe are insulated from the surrounding using fiber glass, as shown in Figure 1(b). The thermocouple sensor is connected to a reader, in which the measured temperature can be stored and retrieved later. The uncertainty of the thermocouple is ±0.4^{o}C [25]. The solar irradiance has been measured using a solar radiation sensor, SOZ-03 [26]. The measurement is done for each experiment throughout the day from 10:00 am to 2:00 pm. Measurements were also taken every ten minutes for the two devices of the same size and under the same environmental conditions. The two units have been tested under the same operating conditions, without any modifications, as a similarity check and the results are shown in Figure 2. The temperature of the heat pipe in case of the reference collector and the second collector, i.e. the collector to be modified, are almost the same, which indicates that the two collectors are close to being identical.

Table 1
Dimensions of the parabolic trough solar collector that is used in the performed experiments

Content	Value
Length	170 cm
Width	80 cm
Depth	35 cm
Inclination Angle	30^{o}
Focal height	11.43 cm
Rim angle	121°
Diameter of the evacuated tube	5.8 cm
Length of the evacuated tube	180 cm

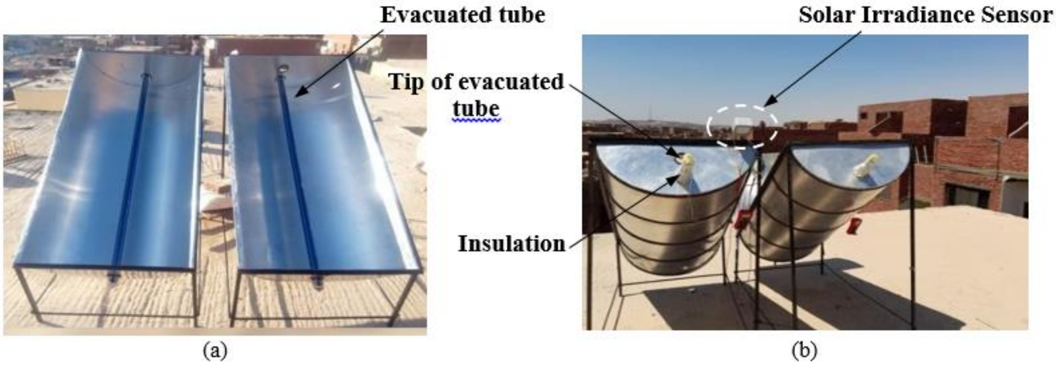

Fig. 1. (a) Front view of the two identical parabolic trough solar collectors, one as a reference (left), and the other in which modifications are implemented (right). (b) Back view of the collectors with the temperature measuring points, which is at the tip of the evacuated tube

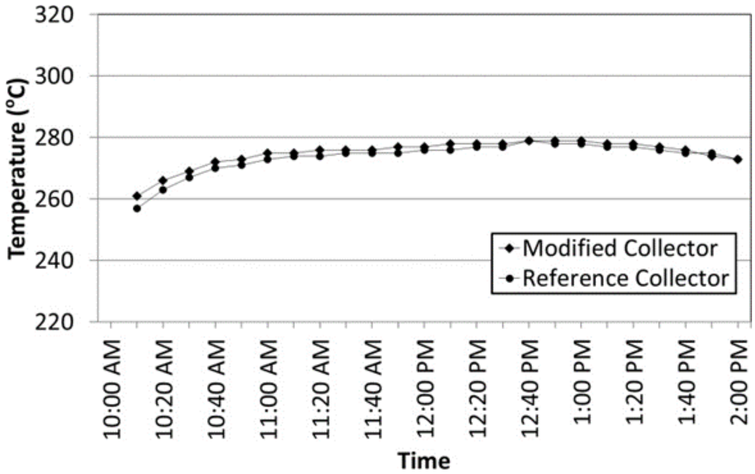

Fig. 2. Temperature at the tip of the evacuated tube in case of a reference collector and the modified collector

2.2 Performed Experiments

All performed experiments have been done in Aswan, Egypt, which is at a latitude of 27°, in July 2021. Four experiments have been performed. The influence of the secondary reflector on the performance of the PTSCs with evacuated tube is examined in both of the first and second experiment. The secondary reflector in the first experiment is installed horizontally, while in the second experiment is installed vertically, as shown in Figure 3. The secondary reflector is installed perpendicular to the primary reflector, and the dimensions of the secondary reflector are given in Table 2. The temperature of the heat pipe and the solar irradiance are measured for both collectors, i.e. the reference collector and the collector with a secondary reflector. In the third and fourth experiments, an aluminum foil is used to cover the surface of the PTSC unit, and the results are compared to the reference of unit in which a reflective surface of polished aluminum is used. A photo of the PTSC with aluminum foil attached to the galvanized steel surface of the collector is shown in Figure 4. It can be seen that the aluminum foil is well attached to the steel surface and there are no wrinkles in the aluminum foil. The aluminum foil is glued to the steel surface of the PTSC using epoxy, and then both the aluminum foil and the steel surface underwent a rolling process to remove any air pockets that occur between the foil and the steel surface of the PTSC. In the fourth experiment, the effect of covering the surface of the PTSC with aluminum foil, and attaching a secondary reflector on the performance of the collector are examined.

Table 2
Dimensions of the secondary parabolic trough solar collector (SPTSC), which is used in the performed experiments

Content	Value
Length	80 cm
Width	80 cm
Depth	35 cm
Focal height	5.6 cm
Rim angle	121˚

Fig. 3. PTSC with a secondary reflector installed on the primary reflector either (a) vertically or (b) horizontally. The secondary reflector is perpendicular to the primary reflector

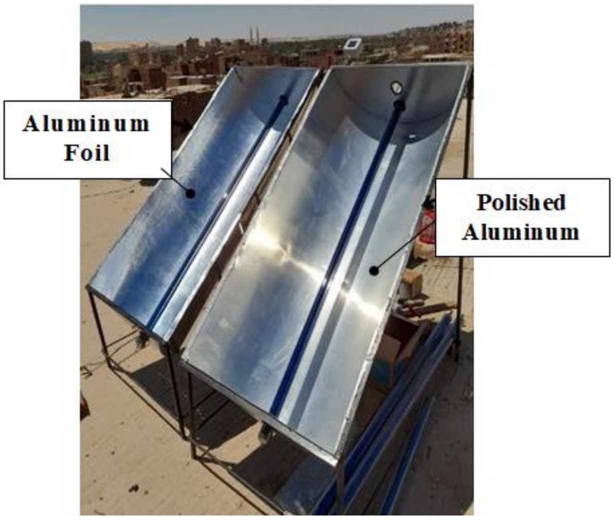

Fig. 4. A photo of the parabolic trough solar collector with a polished aluminum surface (right), and with aluminum foil glued to the steel surface of the collector (left)

3. Experimental Results

3.1 Influence of Using a Secondary Reflector on the Performance of PTSCs

The temperature of the bulb of the heat pipe as a function of time in case of using a secondary reflector is shown in Figure 5. The secondary reflector is tested in case of being installed horizontally and vertically. The temperature of the heat pipe bulb has reached to approximately 300°C, and that is a quite high temperature. This is due to both of the strong irradiance at the time and place of experiment and the high ambient temperature in Aswan city of Egypt. It can be concluded from Figure 5(a) that the temperature of the heat pipe bulb in case of a secondary reflector installed horizontally is close to the temperature of the reference collector, i.e. the collector without a secondary reflector, such that the average temperature difference between the two collectors is about 7°C, which is about 2.5% increase from the average temperature of the reference collector. However, the temperature of the heat pipe bulb in case of a secondary reflector installed vertically is higher than the temperature of the reference collector, as can be seen in Figure 5(b), such that the average temperature difference between the two collectors is about 20°C, which is about 7% increase from the average temperature of the reference collector. The average temperature difference between the collector with a secondary reflector and the reference collector has increased from 7°C, in case of a horizontal reflector, to 20°C in case of a vertical reflector. It can be concluded that adding a secondary reflector should be vertically mounted and not horizontally, in order to maximize the energy reflected to the primary collector.

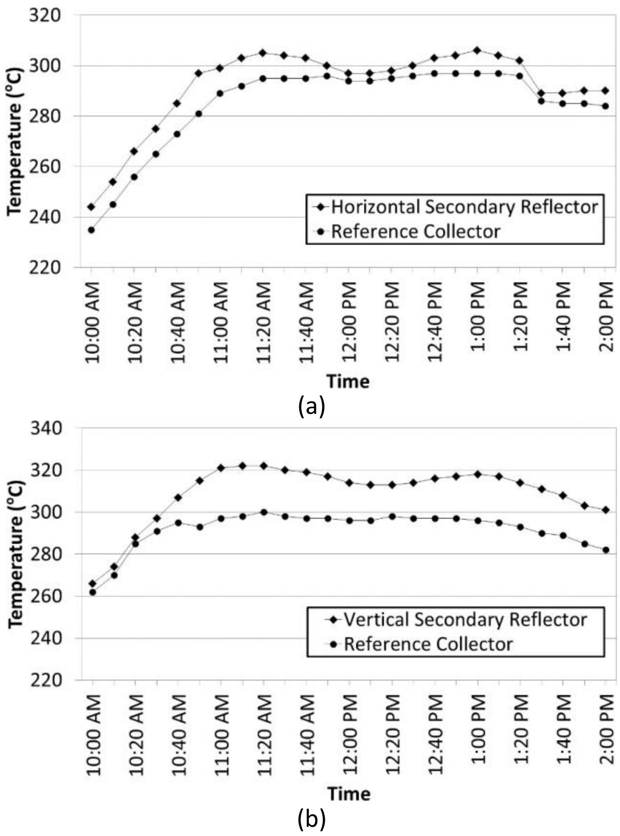

Fig. 5. The temperature of the heat pipe bulb in case of not using a secondary reflector, i.e. the reference collector, and using a secondary reflector oriented (a) horizontally, and (b) vertically

3.2 Influence of Using an Aluminum Foil and a Vertical Secondary Reflector on the Performance of PTSCs

The temperature of the heat pipe bulb as a function of time in case of (a) covering the PTSC with aluminum foil, and (b) using an additional secondary reflector, also covered with an aluminum foil, are presented in Figure 6. In both cases the results are compared to the reference PTSC. The reflecting surface of the reference PTSC is polished aluminum. It can be concluded from Figure 6(a) that covering the surface of the PTSC with aluminum foil has increased the heat pipe bulb temperature in comparison to the reference collector. It is noticed that the average temperature difference between the two collectors is about 15^{o}C, which is nearly 5% increase from the average temperature of the reference collector. The reflectivity of the aluminum foil is greater than the reflectivity of polished aluminum [21], which accounts for the improvement of the heating capability of PTSC. However, adding a secondary vertical reflector to the PTSC, such that both reflectors, i.e. primary and secondary reflector, are both covered with aluminum foil has increased the temperature difference between the modified collector and the reference collector, as shown in Figure 6(b). The average temperature difference between the modified collector, i.e. the PTSC with a secondary vertical reflector, and the reference collector is 30^{o}C, which is nearly 11% increase from the average temperature of the reference collector. It can be concluded that adding a secondary vertical reflector to the PTSC and covering both reflectors with aluminum foil improve the heating capability of the collector.

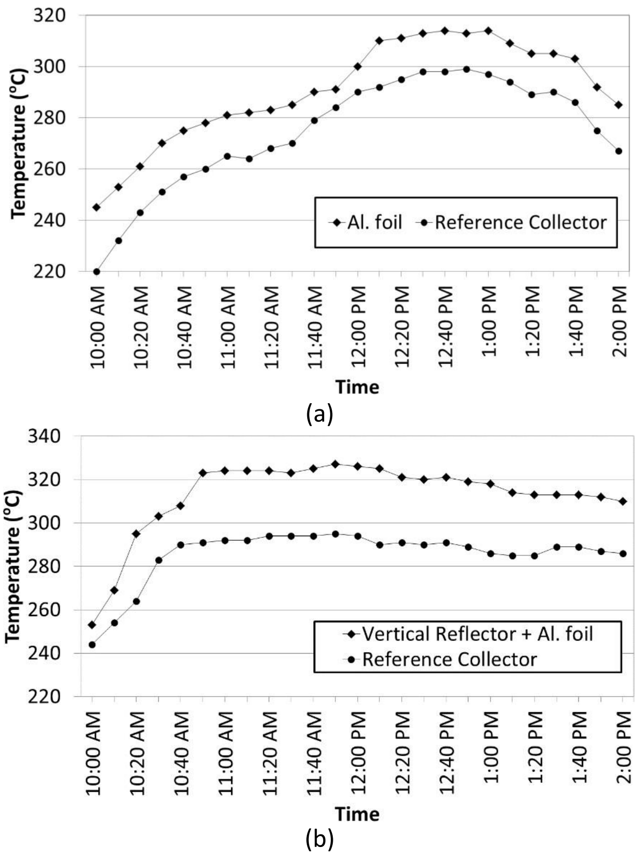

Fig. 6. The temperature of the heat pipe bulb in case of (a) covering the PTSC with aluminum foil, and (b) using an additional secondary reflector that is also covered with an aluminum foil

4. Conclusions

It can be concluded from the performed experiments that

i. Adding a secondary reflector at the bottom of a parabolic trough solar collector (PTSC) should be vertically mounted and not horizontal, in order to maximize the energy reflected to the primary collector.
ii. The heating capability of the PTSC can be improved by adding a secondary vertical reflector at the bottom of the collector and covering both reflectors, i.e. the primary and the secondary reflectors, with aluminum foil.
iii. The temperature of the heat pipe bulb of the PTSC has increased by nearly 11% above the temperature of the conventional PTSC collector, due to adding a secondary vertical reflector to the collector and covering both the primary and the secondary reflectors with aluminum foil.
iv. The aluminum foil has become stronger, homogenous, durable, scratch-resistant and highly reflective by gluing it using epoxy to the surface of the PTSC, and then rolling the surface to remove any air pockets that exist between the foil and the steel surface of the collector.

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