Design of a Closed Parabolic Trough Solar Concentrator Test Facility*

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Abstract*– Solar energy is an infinitely renewable energy source with enormous potential for replacing fossil fuels to address many energy industry issues, including rising energy consumption, fuel depletion, and global warming. As an efficient and cost-effective concentrating solar power (CSP) technology, the parabolic trough collector (PTC) is one of the most established technologies that is widely used for high-temperature applications (up to 400°C). A recently growing research trend investigates different reflector-enclosed PTC designs to protect PTCs from sand storms and dust deposition. Closed PTC is a promising technology that can be constructed using local resources with acceptable thermal performance. In the present work, a multi-tasked closed PTC test facility is designed and constructed not only to boost thermal efficiency but also to be modular for research purposes. The introduced closed PTC is provided with different features that make it more flexible to keep pace with the dynamic nature of scientific research topics.

***Keywords*-- Concentrated Solar Power (CSP), closed parabolic trough, facility, research, thermal efficiency**

I. Introduction

Solar power is an infinite renewable energy source with an enormous potential of fossil fuel substitution to tackle many energy issues, such as the increasing demand for energy, fuel depletion, and global warming [1]. Moreover, concentrated solar power (CSP) can be considered a large radiation reservoir capable of fueling high-temperature systems, enabling it to compete with current fuel technologies [2]. Parabolic trough collector (PTC) is considered the most matured CSP technology utilized in various high-temperature applications (up to 400°C) since it is classified as an efficient and economical technique to concentrate solar power [3].

However, the most considerable solar power available lies within the Sun-Belt area that ranges from the equator (2.38 MWh/m^2) to the latitude of up to 50° (1.29 MWh/m^2) [4], which the same range of the high-latitude dust source [5]. The dust presence and high accumulation levels are not the only challenges confronting real-world CSP units, but also overnight humidity on dusty reflectors leading to muddy-soiled surfaces requiring the use of wet cleaning technologies [6]. In the short term, such cleaning raises the operational costs of the CSP plant since the water is limited and has to be treated, while over the long term, wet cleaning can accelerate the aging of commercially available silver reflectors [7]. Therefore, several studies investigated alternative reflector-enclosed PTC designs.

In order to protect PTCs from sand storms and dust buildup, Bierman et al. [6] have proposed an enclosed PTC design in a modified glasshouse, supplied with an automatic glasshouse roof-top washing mechanism besides air filtration equipment to reduce soiling and related losses significantly. However, the ideal angle of inclination of the glasshouse roof and the related losses in reflection remains uncertain. Another concept suggested a PTC design in which a transparent polymeric film protects the concentrator was investigated by Good et al. [8]. They employed air as a heat transfer fluid (HTF), where the entire concentrator was based on reflective polymers installed on a rigid supporting concrete structure. Alternatively, to limit convective heat loss from the thermal receiver, a closed PTC (CPTC) where a transparent material is used to cover a hermetic concentrator has been suggested theoretically by Fernandez-García et al. [9] and experimentally by Abdel-Hady et al. [10]. The proposed CPTC was much cheaper and lighter in weight than conventional PTCs, as they applied fiberglass (with polyester matrix) as a composite material for building the trough. However, the structure of the glass-covered PTC was deformed more than a glass-free one [10]. Another CPTC was proposed by Zeidan et al. [11] with a steel-based trough structure to minimize deformation with a low-cost stainless steel reflector sheet. Recently, a manually tracked CPTC is tested against uncovered PTC by Upadhyay et al. [12]. They observed that CPTC showed greater experimental efficiency (13.44–13.55%) than manually-tracked uncovered PTC (11.42–12.23%), indicating promising results for CPTC against conventional PTC.

A multi-task CPTC test facility is designed and built for research purposes in the present work, not simply enhancing its thermal efficiency. In order to achieve this aim, an optical study has been carried out, besides different features are added and explained.

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II. SYSTEM DESIGN

A. Parabola Dimensions

The parabola is intended to position the focus point close to the center of the central axis of the parabola to prevent local thermal stress that could damage the glass cover. Then, if a generic parabola ABC with a vertex B at the origin, as shown in Fig. 1, its equation may be stated as follows [13]:

$$x^2 = 4fy = 2by \qquad (1)$$

Where f is the parabola's focal length which is assumed as one-half of distance b. Hence at points A and C, ($y = b$), then ($x = \pm b\sqrt{2}$), which means that the distance ($a = 2b\sqrt{2}$). Another design restriction is considering the parabola arc length (ABC) through applying the following equation [14]:

$$ABC = 0.5\sqrt{b^2 + 16a^2} + (b^2/8a)\ln\left[\left(4a + \sqrt{b^2 + 16a^2}\right)/b\right] \qquad (2)$$

According to the dimensions of the available reflective material sheets in the Egyptian market (1.25×2.5m), and by substitution with the value of ($a = 2b\sqrt{2}$) and an arc length of 1.25m and solving for b, then the values of parabola's geometry can be obtained as listed in Table I.

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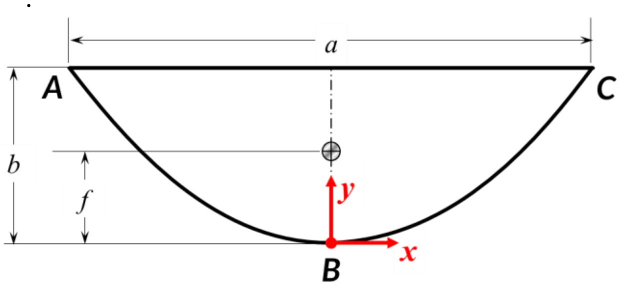

Fig. 1 Geometry of a generic parabola ABC.

TABLE I
GEOMETRIC PARAMETERS OF THE DESIGNED PARABOLA

Parameter	*a*	*b*	*f*
Value (m)	1.000	0.335	0.186

B.Thermal Receiver Design

Incident rays are required to be reflected on the thermal receiver tube with its axis located at the focal length of the designed parabola. To avoid missing reflected rays, a ray-tracing freeware based on the Monte Carlo method, called *Tonatiuh*, is used to simulate the solar radiation concentrated over the receiver tube. Ray tracing allows the recommendation of receiver tube diameter that can collect all reflected rays. Therefore, eight different copper pipes candidates are studied with the assumption of subjecting the trough aperture to 1 kW/m^2 with a transparent glass cover transmittance of 100%. Then according to the calculated received total power on each studied pipe, the optical efficiency can be estimated, as listed in Table II, while the flux distribution over pipes perimeter is illustrated by Fig. 2. According to this optical study, the 1-5/8" pipe has been selected. Finally, the entire design of the CPTC is carried out by SolidWorks 2020 software and illustrated in Fig. 3.

TABLE II
OPTICAL EFFICIENCY OF ALL STUDIED COPPER PIPES CANDIDATES

Nominal diameter (inch)	**Outside diameter ×10^{-3} (m)**	**Optical efficiency % (–)**
3/8"	9.53	94%
1/2"	12.7	95%
5/8"	15.88	95%
3/4"	19.05	95%
7/8"	22.23	96%
1 1/8"	28.58	96%
1 3/8"	34.93	97%
1 5/8"	41.28	98%

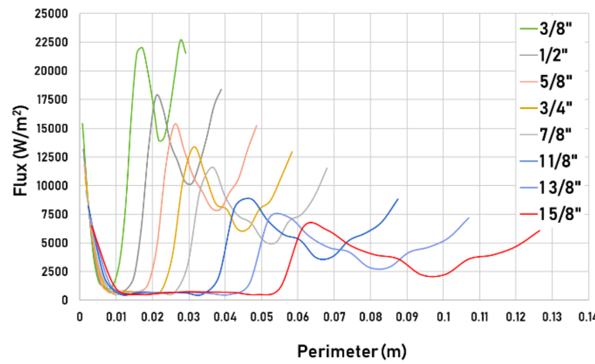

Fig. 2 Flux distribution over pipes perimeter.

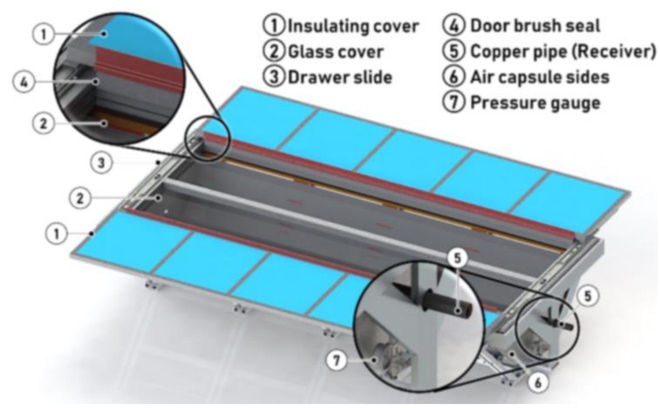

Fig. 3 A render of the entire proposed CPTC design.

C. Reflector Sheet Material

To achieve the maximum thermal efficiency of the CPTC, a reflector sheet with high solar-weighted reflectance should be selected. A comparison between the reflectance of a wide range of materials is proposed by Hafez et al. [15]. As the proposed CPTC design is a test facility, where researchers can test different materials and their influence on the performance of the CPTC, the authors selected polished stainless steel with an average reflectance of 50%, which is the worst-case material among the materials listed in [15]. The reasons behind this are to allow researchers to investigate the performance by changing the material and keep the cost as minimum as possible.

D. Thermal System Analysis

The reflector sheet and air capsule sides are thermally insulated with 30-mm-thick glass wool with a density and thermal conductivity of 75 Kg/m³ and 0.0315 W/mK, respectively, as illustrated in Fig. 4.

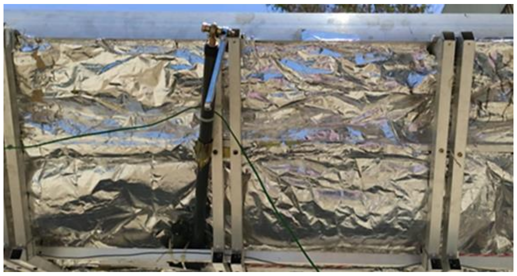

Fig. 4 An image of thermal insulation of the proposed CPTC.

According to this, heat can be lost from the top surface of the CPTC by conduction in the glass cover, followed by convection and radiation from the glass cover surface, and direct radiation losses from air capsule air to the ambient. On the other hand, heat leakage through the reflector sheet and the sides can be controlled by evaluating the heat lost by conduction through the insulation. This portion of heat loss can be neglected when insulating material with low thermal conductivity and large thickness is applied. The thermal model of the CPTC can be represented as indicated by Fig.5.

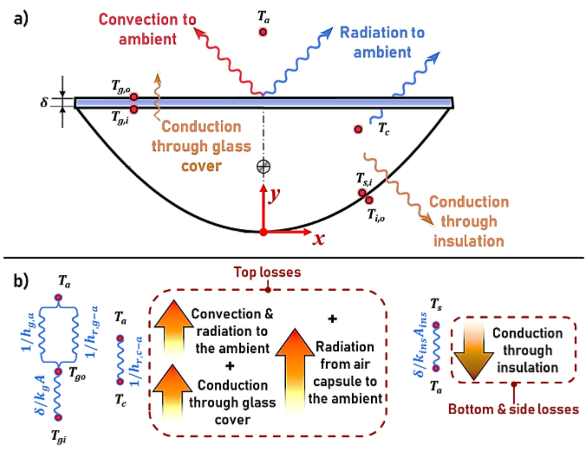

Fig. 5 Representation of thermal losses from the proposed CPTC.
(a) Thermal losses (b) Equivalent thermal resistances

Neglecting the heat lost from sides and reflector sheet, then heat transferred through the glass cover can be determined from:

$$Q_{top} = \left(T_{g,i} - T_{g,o}\right)/R_1 + \left(T_{g,o} - T_a\right)/R_2 + (T_c - T_a)/R_3 \quad (3)$$

Where, $T_{g,i}$, $T_{g,o}$, T_a, and T_c are the inner and outer glass surfaces temperatures, ambient and air capsule temperatures, respectively. Thermal resistances: R_1 , R_2 , and R_3 can be evaluated from the following equations:

$$R_1 = \delta/\left(k_g A\right) \quad (4)$$

Where k_g is the thermal conductivity of the glass cover with thickness, δ, and aperture area, A.

$$R_2 = (R_{conv} \times R_{rad})/(R_{conv} + R_{rad}) \quad (5)$$

And

$$R_{conv} = 1/(hA) \quad (6)$$

$$R_{rad} = 1/\left[\varepsilon_g \sigma A\left({T_{g,o}}^2 + {T_a}^2\right)\left(T_{g,o} + T_a\right)\right] \quad (7)$$

Where h is the convective heat transfer coefficient at the glass cover surface, ε_g is the emissivity of the glass cover, and σ is the Stefan–Boltzmann constant (5.6704×10^{-8} W/m^{2}K).

$$R_3 = 1/\left[\varepsilon_c \sigma A\left({T_c}^2 + {T_a}^2\right)(T_c + T_a)\right] \quad (8)$$

Where ε_c is the emissivity of the air capsule. An image of the built CPTC, with insulating covers removed, is shown in Fig. 6.

Fig. 6 An image of the proposed CPTC (with removed insulating covers).

III. Design Key Features

A. Glass Cover

The glass cover is designed as a hinged door made from an aluminum PS-5606 profile to seal the air capsule and facilitate access to the reflector sheet and the enclosed air capsule for maintenance, fixing measurement probes within the air capsule, and cleaning operations for the reflective surface. In addition, the selection of such aluminum profile allows researchers who use this test facility to study the effect of single- and double-glass cover with different thicknesses, ranging from 6 mm to 10 mm.

B. Insulating Cover

The proposed CPTC is featured with a sliding insulating cover above the aperture glass door. The insulating cover can trap heat inside the air capsule during the absence of solar radiation, either overnight or in cloudy weather. Therefore, using such covers impact on the CPTC thermal performance through minimizing thermal losses can be studied by the present design. Moreover, this cover provides safety to the aperture glass cover from sand storms and dust accumulation besides protecting it from sudden rains, especially when the glass cover is hot due to operation in the daytime. On the other hand, the insulating cover is fitted with longitudinal door brush seals that assist in cleaning the glass cover from any accumulated dust during the system operation.

Furthermore, the insulating sliding cover can also support photovoltaic panels to study their performance or provide the CPTC system with the electric power required to drive the tracking system. Finally, this cover can be removed entirely if not required at all. Photographs of the insulating cover during the building of the CPTC facility are illustrated in Fig. 7.

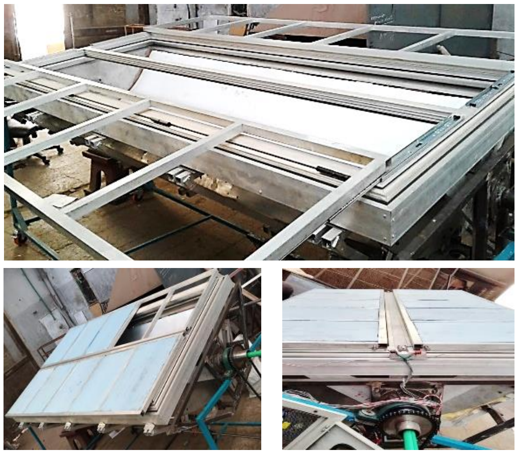

Fig. 7 Images of the insulating cover during CPTC building (closed).

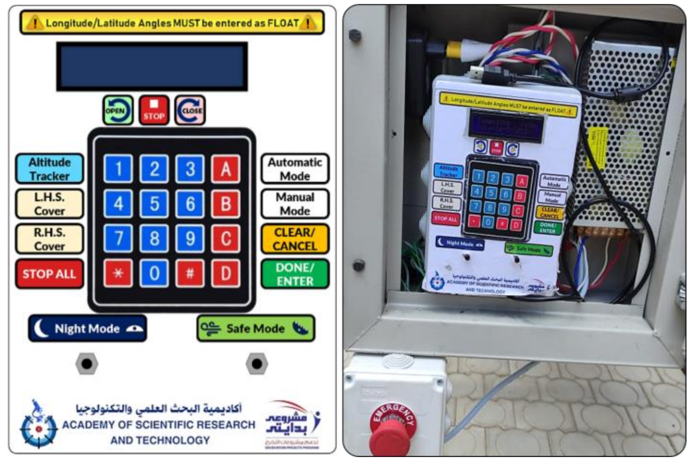

Fig. 9 CPTC control panel.

C. Air Capsule Sides

The sides of the air capsule were made from 3-mm-thick laser-cut stainless steel to be installed on both sides of the air capsule. Stainless steel was selected due to its stiffness and low thermal conductivity. In addition, stainless steel was used to strengthen both sides of the device besides carrying the copper pipe during rotation. The sides are provided with a square hole and a venting hole, as illustrated in Fig. 8. The square hole centroid is located at the parabola focal point. It allows changing the receiver tube diameter simply by replacing just two 0.1×0.1 m stainless pads per each side as spare parts that are holed with the outside diameter of the required thermal receiver outside diameter using laser cutting. The vent hole is attached to a valve and a pressure gauge. This vent can be used to evacuate the capsule or inject specific gas within the capsule instead of air and study the effect on the thermal performance of the CPTC.

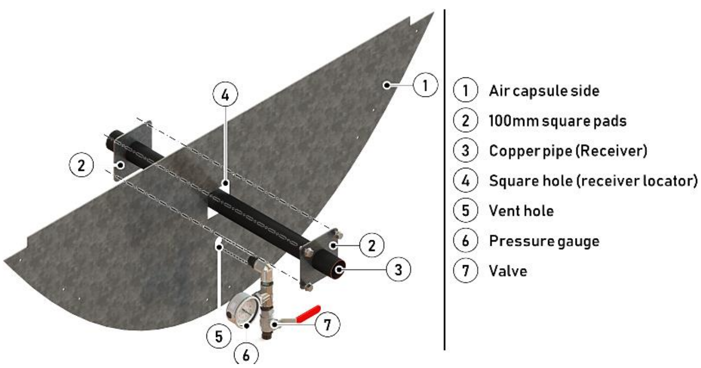

Fig. 8 Air capsule side assembly.

D. Tracking Control Unit

The control unit is designed and carried out to calculate the solar altitude angle based on the date and time, defined by a real-time clock (RTC) unit, and both longitude and latitude angles given by the user through a keypad. Furthermore, the period to update the altitude angle is defined by the user with a value ranging from 1 to 9 minutes, allowing the investigation of the tracking system lag influence on the system performance. The system also is fitted with *Sleep* and *Shut-down* buttons used to close the sliding insulating cover and rotate the CPTC to the face-down position, respectively. The *Sleep* mode can be activated in cloudy periods or sand storms during the daytime operation, while the *Shut-down* mode is applied by sunset. However, these modes are activated manually by pressing the appropriate button in the control panel, as illustrated in Fig. 9, based on the user observations.

All control commands are handled by a microcontroller unit, ARDUINO MEGA 2560. The control unit also supports manual and automatic tracking modes, giving the facility user more flexibility, as illustrated in the flow chart indicated by Fig. 10. In addition, the system receives feedback from an optical encoder for the altitude control motor and limit switches to achieve a more stable tracking system, and the control unit is provided with an *Emergency Stop* button to shut down the entire system in case of any unexpected issue.

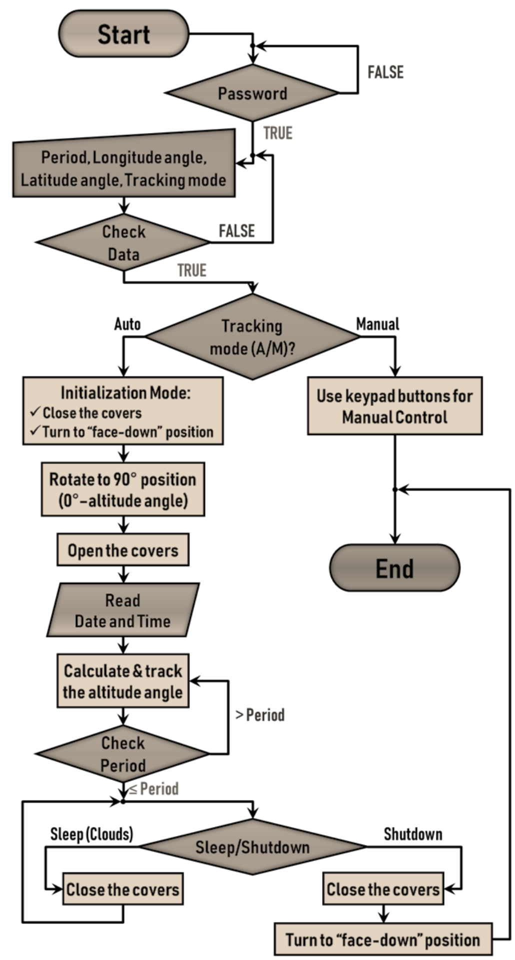

Fig. 10 Control system flow chart.

CONCLUSIONS

Solar energy is an infinitely renewable energy source with enormous potential for replacing fossil fuels. New research trend investigates different reflector-enclosed PTC designs to protect PTCs from sand storms and dust deposition. CPTC is a promising technology that can be constructed using local resources. Therefore, in the present work, a newly developed CPTC test facility is designed and built at the Faculty of Engineering, Mansoura University, Egypt, with various features that make it more adaptable to the dynamic nature of scientific research. The main features of the proposed CPTC design can be summarized in the following:

- *Glass cover*: can be replaced by either different single-glass thicknesses, ranging from 6 to 10 mm, or a double-glass window to study the effect of glass layers characteristics on the system performance. It is also fitted with a hinged aluminum profiled frame to allow easy access to the reflecting sheet, thermal receiver, and air capsule for maintenance, cleaning and fixing measurement probes.
- *Insulating cover*: can trap heat inside the air capsule during the absence of solar radiation, either overnight or in cloudy weather. It provides safety to the aperture glass cover from sand storms and dust accumulation besides protecting it from sudden rains, especially when the glass cover is hot due to operation in the daytime. It also assists in cleaning the glass cover from any accumulated dust during the system operation by fitting it with door brush seals.
- *Air capsule sides*: are made of sturdy 3-mm-thick stainless steel. Each side is provided with a square hole, allowing the model user to change the receiver pipe by replacing just two 0.1-m square stainless pads per side that fit the new receiver outside diameter. Each side also has a vent hole attached to a valve and a pressure gauge, enabling the researcher to evacuate the capsule or inject a specific gas within the capsule instead of air and study the effect on the thermal performance of the CPTC.
- *Tracking control unit*: is designed to calculate the solar altitude angle based on the date and time, defined by an embedded (RTC) unit, while location coordinates are entered manually by the user. As the tracking update period is left to be determined by the user, it allows the investigation of the tracking system lag impact on the system performance. The system is also fitted with *Sleep* and *Shut-down* buttons that close the sliding insulating cover and rotate the CPTC to the face-down position, respectively.
- *Reflector sheet*: can be changed from polished stainless steel to any other reflective material with higher reflectance.

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REFERENCES

[1] E. Bellos and C. Tzivanidis, "Alternative designs of parabolic trough solar collectors," *Prog. Energy Combust. Sci.*, vol. 71, pp. 81–117, 2019, doi: 10.1016/j.pecs.2018.11.001.

[2] G. J. Nathan *et al.*, "Solar thermal hybrids for combustion power plant : A growing opportunity," *Prog. Energy Combust. Sci.*, vol. 64, pp. 4–28, 2018, doi: 10.1016/j.pecs.2017.08.002.

[3] E. Bellos, C. Tzivanidis, and D. Tsimpoukis, "Enhancing the performance of parabolic trough collectors using nano fl uids and turbulators," *Renew. Sustain. Energy Rev.*, vol. 91, pp. 358–375, 2018, doi: 10.1016/j.rser.2018.03.091.

[4] N. S. Tiwana, "Simulation Modeling and Optimization of the Performance of the Solar Water Heating System at the Southland Leisure Centre," University of Calgary, 2017.

[5] J. E. Bullard *et al.*, "High-latitude dust in the Earth system," *Rev. Geophys.*, vol. 54, pp. 447–485, 2016, doi: 10.1002/2016RG000518.Received.

[6] B. Bierman, J. O. Donnell, R. Burke, M. Mccormick, and W. Lindsay, "Construction of an enclosed trough EOR system in South Oman," *Energy Procedia*, vol. 49, pp. 1756–1765, 2014, doi: 10.1016/j.egypro.2014.03.186.

[7] C. Sansom, A. Fernández-García, F. Sutter, H. J. A. Almond, P. King, and L. Martínez-Arcos, "Soiling and Cleaning of Polymer Film Solar Reflector," *Energies*, no. November, 2016, doi: 10.3390/en9121006.

[8] P. Good, G. Ambrosetti, A. Pedretti, and A. Steinfeld, "A 1.2 MWth solar parabolic trough system based on air as heat transfer fluid at 500 ° C — Engineering design , modelling , construction , and testing," *Sol. Energy*, vol. 139, pp. 398–411, 2016, doi: 10.1016/j.solener.2016.10.002.

[9] A. Fernandez-García, E. Rojas, M. Perez, R. Silva, Q. Hernandez-Escobedo, and F. Manzano-Agugliaro, "A parabolic-trough collector for cleaner industrial process heat nzazu Fern a d," *J. Clean. Prod.*, vol. 89, pp. 272–285, 2015, doi: 10.1016/j.jclepro.2014.11.018.

[10] F. Abdel-Hady, S. Shakil, M. Hamed, A. Alzahrani, and A.-H. Mazher, "Design, Simulation and Manufacturing of an Integrated Composite Material Parabolic Trough Solar Collector," *Int. J. Eng. Technol.*, vol. 8, no. 5, pp. 2333–2345, 2016, doi: 10.21817/ijet/2016/v8i5/160805005.

[11] E.-S. B. Zeidan *et al.*, "Design and Investigation of a Closed Parabolic Trough Performance," in *25th SolarPACES Conference*, 2019.

[12] B. H. Upadhyay *et al.*, "Design, development and techno economic analysis of novel parabolic trough collector for low-temperature water heating applications," *Case Stud. Therm. Eng.*, vol. 26, p. 100978, Aug. 2021, doi: 10.1016/j.csite.2021.100978.

[13] A. Gustafson, P. D. Frisk, and J. Hughes, *College Algebra*, 10th Ed. Cengage Learning, 2010.

[14] M. R. Spiegel, S. Lipschutz, and J. Liu, *Mathematical Handbook of Formulas and Tables*, 4th Ed. McGraw-Hill Companies, Inc., 2013.

[15] A. Z. Hafez, A. Soliman, K. A. El-Metwally, and I. M. Ismail, "Solar parabolic dish Stirling engine system design, simulation, and thermal analysis," *Energy Convers. Manag.*, vol. 126, pp. 60–75, Oct. 2016, doi: 10.1016/j.enconman.2016.07.067.