Renewable and Sustainable Energy Reviews 91 (2018) 822–831

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

# Review of solar parabolic-trough collector geometrical and thermal analyses, performance, and applications

Ali Jaber Abdulhamed[a,b,*], Nor Mariah Adam[a], Mohd Zainal Abidin Ab-Kadir[a], Abdul Aziz Hairuddin[a]

[a] Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, University Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia
[b] Automotive Department, College of Engineering/AL-Musaib, University of Babylon, Hilla, Babylon, Iraq

ARTICLE INFO

*Keywords:*
Parabolic trough collector
Geometry analysis
Thermal analysis
Performance
Solar energy

ABSTRACT

By year 2030, the world's energy demand is expected to increase by over 60% of current demand. Thus, the potential of renewable energy should be investigated. Renewable energy is the energy from natural and unnatural available forms including wind, biomass, solar, and waste heat energy generated through various human activities. Solar energy is an available and clean form of renewable energy used as an alternative to fossil fuel in generating energy. However, the maximum extraction of thermal energy from the sun is most challenging. This study focuses on energy generation using the parabolic trough collector (PTC). This review contains geometrical analysis including the thermal approach of the PTC model, heat transfer, and method of enhancing thermal efficiency on the PTC receiver. This paper also includes performance analysis, thermal efficiency, and applications of the solar-powered PTC and the history of PTC evolution. The PTC applications include desalination process, air heating system, power plants, refrigeration, and industrial heating purposes. This paper benefits researcher that focus on the solar-powered PTC.

## 1. Introduction

Many countries have embarked on the use of renewable energy currently because of the growing energy demand and lack of non-renewable energy used in refrigeration, air and water heating, large-scale and small-scale industries, desalination, and electric power generation. Moreover, the demand for fresh water will increase as a result of climate change, population growth, and improved living standards. Solar energy is the most easily available abundant source of energy on earth for the lighting of houses, generation of thermal power, and in applications of industrial heating. Numerous countries with high levels of solar radiation, such as Egypt, India, Mexico, Morocco and USA, are focusing on solar power for electricity. In the 1980w, 9 PTC plants were constructed in the Mojave Desert (California, USA) [1]. The fuel used in the desalination process is limited, cost, and the increased air pollution. Distillation of fresh water by solar still system are some of the best practical technologies implemented in several countries [2].

A solar collector can absorb the sun's irradiation and process it to heat energy, thereby converting it to thermal energy into working fluid which can be water, air, or oil. Working fluid thermal energy can be used directly for various applications. Solar collectors have different types such as the Parabolic Trough Collector (PTC), Flat-plate collector, and Compound parabolic collector (CPC). Flat plate collectors are usually utilized to generate hot water due to its temperature range at approximately 120–140 °C. The temperature of the PTC receiver tube can be as high as 350–400 °C [3]; thus, it can be used as a steam generator for power plants and the desalination process. A typical power plant generally requires massive fossil fuel resulting in large carbon dioxide ($CO_2$) emissions. Therefore, the use of available renewable energy will help reduce non-renewable energy consumption and pollution. Owing to the efficiency of the solar parabolic collector, which highly depends on concentration ratio ($C$) [ratio of the aperture area ($A_a$) to the receiver surface ($A_r$)], and also the PTC's higher heat absorption compared with that of the flat plate collector, this paper focuses on the PTC with high temperature range and concentration ratio.

In this review, we emphasizes geometrical analysis, thermal mathematical design, thermal efficiency, applications, and experimental setups of the collector/receiver of a Parabolic Trough Solar Powered Collector in terms of temperature, heat flux, heat loss, and ambient conditions. This study presents the PTC design criteria, materials, and heat transfer enhancement technologies as well as the thermal performance of PTC to identify the aspects that should be considered in future developments and to facilitate a means for students and researchers to study this area.

* Corresponding author at: Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, University Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia.
*E-mail address:* ali_alkhakani@yahoo.com (A.J. Abdulhamed).

https://doi.org/10.1016/j.rser.2018.04.085
Received 29 January 2017; Received in revised form 9 March 2018; Accepted 14 April 2018
1364-0321/ 

## 2. History of PTC

The initial idea for a solar concentrator was to employ a semi-spherical surface saturated with many small mirror sections. The focal point of a spherical mirror would be located at half of the spherical section's, directly above the vertex of the sphere. The first plan was to use the derivative of a circular equation to determine the proper incline at various points along the sphere's inner surface; then, the inclines would be rotated to the origin. The radiation from the sun would be reflected back to the focal point, as in the case of a parabola. In 1870, the first practical experience with PTCs belonged to John Ericsson (a Swedish engineer immigrant to the United States), who designed and constructed a collector with an aperture area of (3.25 $m^2$) to produce steam for drive a small (373 W) engine. He also built (from 1872 to 1875) seven similar systems with air as working fluid [4]. In 1936, C.G. Abbot utilized a PTC to convert solar energy into mechanical power and operate a (0.37 kW) steam engine [4]. After two years in Florida, he utilized a similar PTC to generate a (0.15 kW) steam engine. Abbot also proved that the system should obtain a theoretical overall efficiency of (15.5%) and actual efficiency of (11.7%) to produce steam at (225 °C) by using PTC [5].

The interest in the technology of solar focusing has been negligible for more than 60 years. However, in response to the oil crisis of the 1970s, alternative energy sources have attracted international attention to supplement fossil fuels; therefore, numerous PTC systems have been developed. In 1970, the United States (U.S.) Government's Sandia National Laboratories has designed the first two collectors in the U. S., and worked at temperatures below 250 °C. In July 1975, three PTCs were constructed and tested in the U.S. with (7.8 $m^2$) aperture area and (90°) rim angle. The PTC was equipped by (4 cm) diameter chrome-coated carbon-steel receiver tube with a 1-cm evacuated annulus [6]. After 1980, this technology entered the market [7]. In 2010, Southeast University and Sanle Electronic Group of China created the first PTC with a Sanle-3 HCE receiver tube, which showed good performance and reliability [8].

Simulation studies on PTC systems have been widely achieved. Some of them have been based on the first law of thermodynamics in performance analysis, whereas others have been designed analytically according to the second law of thermodynamics [9]. Multi-dimensional design was developed through performance analysis to explain the flow and heat transfer of the collector and receiver [10]. An analytical method was established to estimate the flux density from the reflector surface areas to the receiver surface [11]. Jeter et al. used a semi-finite analytical formulation to develop a relationship for estimating the distribution of concentrated flux density in PTC [12].

Most aforementioned designs were based on the assumption that the solar flux and flow were uniform or constant in the PTC receivers, and many correlations in the designs were also based on uniform or constant temperature assumption. The flow is heated asymmetrically and thus is non-uniform due to the nature of non-uniform solar flux on the outer receiver tube surface. Eck et al. developed a three-dimensional model by using Finite Element Method (FEM) with non-uniform solar heat generation distribution received from radiation tracing simulations, which presented a good agreement with available measurements [13].

## 3. Geometry analysis of a PTC

### 3.1. Mathematical model

Concentration ratio ($C$) is the ratio of the collector aperture area ($A_a$) to the receiver area ($A_r$), which are the factors increasing the radiation flux on the energy-absorbing surface. Concentration ratios vary from low values of less than unity to the high values of $10^5$ [14–16].

$$C = A_a/A_r \tag{1}$$

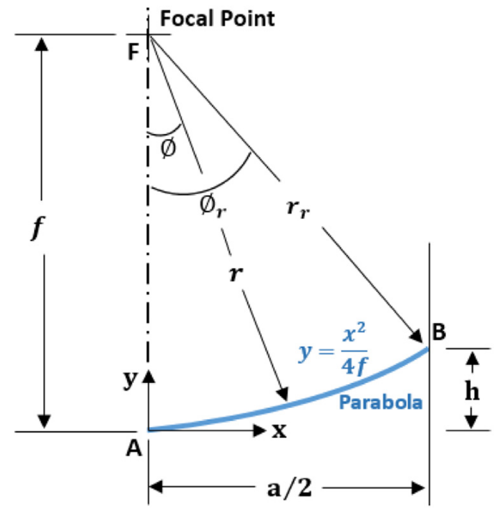


**Fig. 1.** Section of a linear parabolic concentrator showing major dimensions and the x, y coordinates [21].

Fig. 1 presents the cross-sections of a linear parabolic concentrator; and the parabola equation for the coordinate system is [1,17–20]:

$$y = (1/4f)x^2. \tag{2}$$

Term ($a$) is the aperture and focal length ($f$) is the distance from the focal point to the vertex. In Fig. 1, the radiation beam is located on the reflector at Point B. The rim angle ($\varnothing_r$), described by AFB, provides the maximum mirror radius ($r_r$). Rim angle affects the incoming sun radiation and the manufacturing of the parabolic collector [19], whereas the rim angle is written as follows:

$$\varnothing_r = tan^{-1}\{[8(f/a)]/[16\,(f/a)^2 - 1]\} = sin^{-1}(a/2r_r) \tag{3}$$

The local mirror radius at any point of the parabolic reflector is [15]:

$$r = 2f/(1+\cos\varnothing) \tag{4}$$

Arc length ($L$) can then be estimate as [22,23]:

$$L_{arc} = \quad 2f\{[\sec(\varnothing_r/2)\tan(\varnothing_r/2)] + [\ln(\sec(\varnothing_r/2)\tan(\varnothing_r/2))]\} \tag{5}$$

In addition, PTC depth is [19]

$$h = a^2/16f \tag{6}$$

The efficiency of the solar thermal collector is measured by estimating the inlet and outlet temperatures ($T_{in}$ and $T_{out}$) of a heat transfer fluid passing through the collector. Therefore, the efficiency can be written as [17,24–26]

$$\eta_c = [\dot{m} \quad \times \; C_p \times (T_{out} - T_{in})]/[A_a \quad \times \; I_b] \tag{7}$$

### 3.2. PTC receiver thermal analysis

Three types of heat transfer occur in the PTC receiver with glass cover tube, conduction, convection, and radiation. Convection heat transfer is the transfer of heat from one place to another through fluid movement. This transfer depends highly on the fluid properties, geometry, and roughness of container surfaces [27]. Three processes occur on the convection heat transfer in the PTC receiver: between the inner surface of the absorber tube and the heat transfer fluid [27–32], between the external surface of the absorber tube and the glass cover wall [29–31], and between the glass envelope and the atmospheric environment. Heat convection between the glass cover and ambience is highly dependent on wind, which produces force convection and increases heat losses [27–29,33] as shown in Fig. 2. Conduction heat transfer is the flow of thermal energy from a higher to a lower

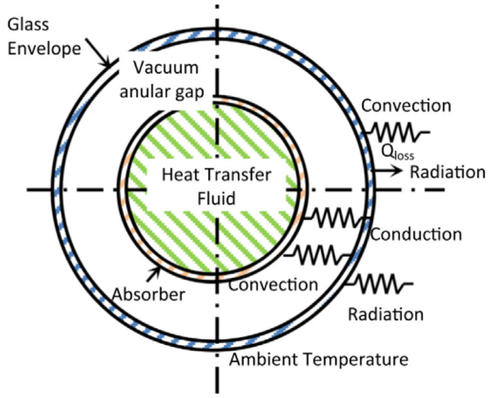


**Fig. 2.** Cross-sectional scheme of a PTC receiver for the Heat Transfer Mode [37].

temperature wall. In a PTC receiver, heat transfer conduction manifests in four forms: conduction heat transfer through the wall of the receiver pipe; conduction heat transfer through the envelope; conduction through the steel absorber and glass cover walls [27,29,30,34]. Radiation heat transfer can be reflected, absorbed, or transmitted, producing an exchange in the radiant energy. Radiation can be studied in two parts: between the receiver pipe and the glass cover and between the glass cover wall and the sky [35,36] as shown in Fig. 2.

### *3.3. PTC receiver thermal development*

Numerous studies have focused on developing thermal efficiency in the receiver tube. Zou et al. presented a small-sized PTC for water heating in cold areas. The novel use of a U-tube absorber is covered by a black finned aluminum tube as shown in Fig. 3. The artificial black finned tube significantly improves the absorptivity of the receiver. Results showed improved thermal efficiency and productivity [38].

Zhang et al. experimentally investigated a double glazing vacuum U-type PTC receiver with water as the working fluid to enhance thermal efficiency [35]. Fuqiang et al. designed and fabricated an asymmetrical outward convex corrugated tube to increase the reliability and heat transfer coefficient of the absorber tube as shown in Fig. 4. Results indicated reduced thermal strain and enhanced heat transfer performance by 148% [39].

Hegazy suggested a new absorber tube comprising of two external longitudinal fins to increase conduction heat transfer from the longitudinal fins to the receiver tube. Findings demonstrated greater thermal efficiency compared with conventional receiver tube [40]. Researchers have presented a thermodynamic design of PTC with an inserted twisted tap (in different twisted tape geometry) in the absorber tube to increase heat transfer coefficient as shown in Fig. 5. The model is validated using experimental data. Results showed greater Nusselt number and thermal efficiency compared with an empty tube [41–53].

Eiamsa-ard et al. experimentally determined the effects of a single-twisted tape, twin-counter (co-twisted tapes) and counter (co-swirled tapes) on Nusselt number (Nu), thermal enhancement, and friction factor (*f*) as shown in Fig. 6 [54]. Tests were conducted with four different twist ratios (y/w), (2.5, 3.0, 3.5, and 4.0). Experiment results proved that Nusselt number, thermal enhancement, and friction factor were raised with reduced twist ratio. Furthermore, twin counter twisted tapes were more efficient than twin co-twisted tapes in enhancing heat transfer [54].

Mwesigye et al. inserted a perforated plate to test the performance of a PTC receiver [55,56]. Zhang et al. examined the effect of diameter ratio (Rd) of the PTC receiver on the thermal performance of the circulation steam generation system. Rd is the ratio between the receiver's internal diameter ($D_{rec}$) to the connecting tube ($D_{con}$) ($Rd{=}D_{rec}/D_{con}$) (Fig. 7), varying from 1.0 to 2.0. The result indicates enhanced heat transfer inside the PTC receiver when the diameter ratio was increased to 1.2 and the optimum Rd was found to be 1.4 with a 12.2% enhancement of heat transfer coefficient [57].

Wang et al. studied the effect of PTC receiver glass cover change from circular to elleptic cross-section area on heat flux distribution gradient. Numerical analysis was done using the Monte Carlo Ray Tracing (MCRT) method. Findings indicate a 32.3% reduced heat flux gradient using an elleptic cross-section area cover glass [58]. Many researchers have utilized wire-coil inserts in PTC to investigate the pressure drops and the heat transfer behavior of the absorber tube. The turbulence inside the tube increased when wire coils were inserted, and the Nusselt number could be increased from 104% to 330% [59–61]. Choudhari and Taji studied the effect of changing the material of the wire coil inserts (aluminum, copper, and stainless steel) on friction factor and heat transfer of the double pipe heat exchanger. They found that copper wire coil has the highest heat transfer rate among two other materials [62]. Amina et al. presented a 3D numerical investigation of heat transfer in a PTC receiver with longitudinal fins using different kinds of nanofluid [63]. Nanan et al. conducted a numerical experiment for forced convective heat transfer behaviors in a tube inserted with baffle tabulators (straight cross-baffles, typical straight baffles, straight alternate-baffles, alternate twisted-baffles, twisted baffles, and twisted cross-baffles) as shown in Fig. 8 [64].

Waghole et al. utilized twisted tape inserts and silver Nano fluid inside the absorber tube of PTC to enhance heat transfer [65]. Hong et al. used a spiral grooved tube fitted with twin overlapping twisted tapes to increase the Nusselt number as shown in Fig. 9 [66].

## 4. PTC performance analysis

Solar-powered PTC consists of a parabolic reflector plate, working fluid chamber (absorber or receiver), and a concentric transparent cover. The receiver [also known as a heat collection element (HCE)] [18,67] is placed at the focal line of the parabolic concentrator. The absorber material should be selected with a low emittance for temperature range and a high absorption for solar radiation such as copper and stainless steel materials [68]. The transparent cover protects the receiver tube from oxidation and heat losses due to wind velocity. To reduce the convection losses within the receiver, the vacuum in the heat collection element (HCE) (receiver tube), should be located in or below

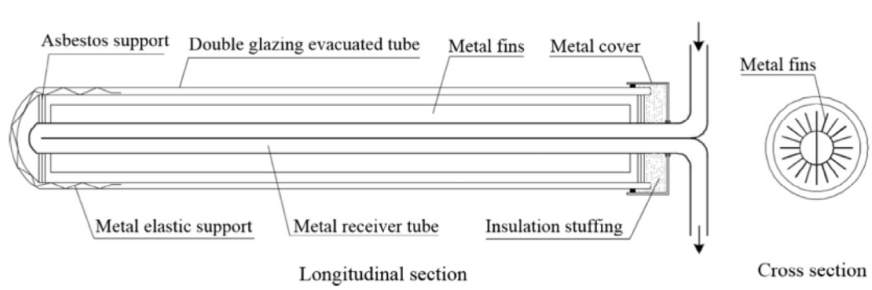


**Fig. 3.** Structure of the receiver tube [38].

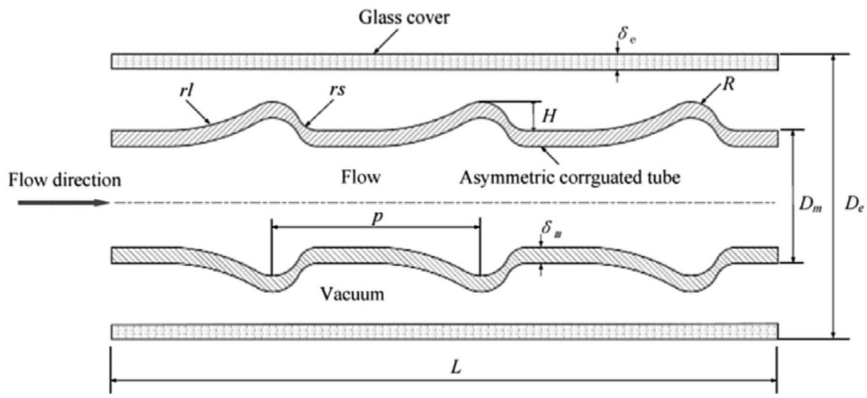


**Fig. 4.** Schematic view of corrugated tube [39].

the Knudsen gas conduction range and typically maintained at about 0.013 Pa (0.0001 mm Hg) [18]. The parabolic collector is fixed on a structure using a solar tracking mechanism that turns the parabolic concentrator with sun movement.

Garcia-Cortes et al. have concentrated on the PTC's reflector geometry and intercept factor with a rigid PTC link, where the theoretical design shape of the trough geometry is directly related to the intercept factor [1]. Paetzold et al. recommended increasing the depth of the collector to turn it into a receiver shelter and protect it from strong winds, thereby reducing thermal losses. However, the effect of wind on the collector would also increase [69–71]. Lüpfert et al. studied and designed a new support structure (torque box) of the PTC. The torque box design has less collector structure deformation and lower weight than the other designs. Therefore, thermal losses and installation costs would be reduced in the future when the total number of drives (gear drive and hydraulic drive) is decreased by connecting more collector elements in one drive [3]. Naeeni and Yaghoubi (2007) studied the wind flow performance analysis of PTC. The big problem of large PTCs is their stability to track the sun and the stability of its collector structure which may face strong winds. Computation study was achieved with various wind velocities of 2.5, 5, 10, and 15 m/s and variable collector angles with respect to wind directions [72], the effect of wind flow field on receiver tube was negligible, whereas the force of wind acting on the PTC structure was normal, and the force acting on the PTC aperture area was 15–20 times higher than that around the PTC [10,72,73]. Zhang et al. showed that strong wind affects the concentration accuracy of PTC by presenting a computational fluid dynamics numerical study [74]. Padilla et al. analyzed the one-dimensional heat transfer on the solar receiver of PTC. The study reduced heat loss by 41.8% due to improved performance, with the receiver covered by an anti-reflective evacuated glass tube to protect the receiver tube from wind velocity and to reduce heat loss [68]. The evacuated glass tube was used to protect the absorber surface from oxidation and to reduce heat loss [18].

Price described the technique of utilizing an infrared camera (IR) to measure the thermal performance of a parabolic trough absorber tube in solar power plants and to show the benefit of using IR as replacement to evaluate numerous receivers over a short time after a long period of operation [75]. Edenburn compared theoretical evaluation with the experimental results for the performance analysis of the cylindrical parabolic collector. Irradiation exchange, radiation transfer, convective and conductive losses, and energy transferred to a working fluid passing through the receiver tube are considered in the performance analysis; the collector can also fully track the sun movement [76].

Kalogirou conducted environmental problem analysis in relation to the utilization of conventional energy sources in order to prove that using solar thermal power in power plant may save approximately 24% of coal consumption [77]. Gang et al. proposed a new solar thermal electric generation technique with low temperature based on compound parabolic concentrator (CPC) and Organic Rankine Cycle (ORC). Results showed improved thermal collector and focusing efficiency [78,79]. Venegas-Reyes et al. presented a novel theoretical and experimental model of PTC with a rim angle of 45°. The PTC thermal performance was calculated according to the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) 93–1986 (RA 91) standard. Results indicated the development of PTC thermal behavior [80]. Jaramillo et al. designed, constructed, evaluated, and tested five aluminum solar PTCs for hot water generation. Two of them were designed with a 45° rim angle and the other three with a 90° rim angle. The thermal test for both designs was determined based on the Standard ASHRAE 93–1986 (RA 91). Maximum efficiency was calculated for collectors with a rim angle of 90° is 67%, whereas maximum efficiency achieved for solar collectors with a rim angle of 45° is 35% [81]. All these analyses would encourage innovation among solar equipment manufacturers, solar energy producers, and policy makers sustainable solar energy development.

## 5. Solar PTC thermal efficiency

A literature review on PTC thermal analysis was also conducted.

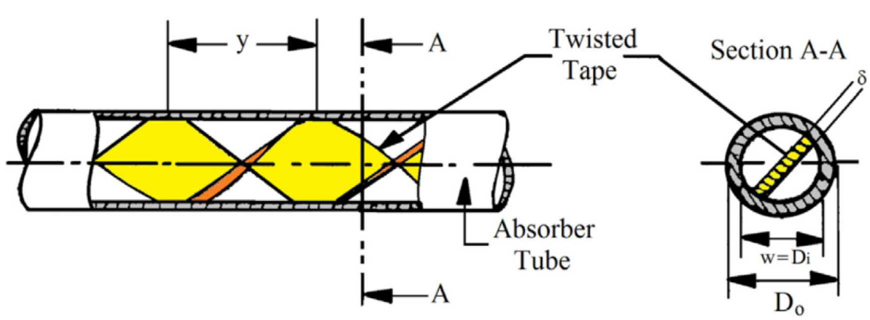


**Fig. 5.** Schematic representation of the twisted tape insert [41].

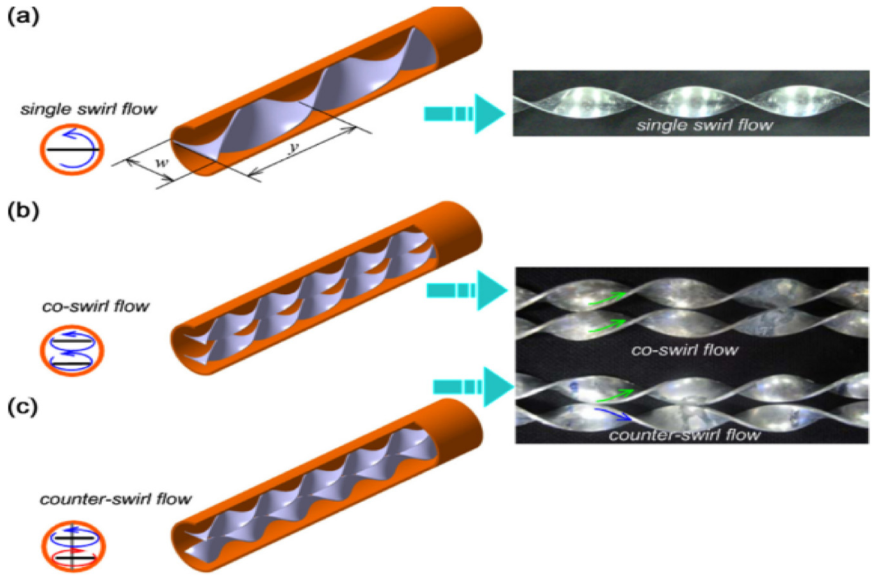


**Fig. 6.** Test tube with twisted tape inserts: (a) single twisted tape, (b) twin co-twisted tapes and (c) twin counter twisted tapes [54].

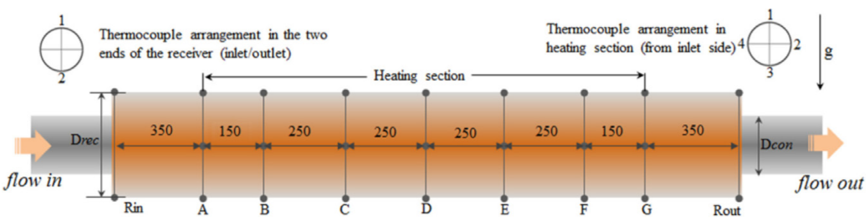


**Fig. 7.** Fabrication of the receiver tube and the arrangement of thermocouple [57].

Tracking system is one of the most important parameters in improving thermal efficiency. The solar tracking device maintains the parabolic trough collator toward the sun's direction during the day to receive solar radiation. Geyer and Lüpfert (2002) improved two high performance Eurotrough (ET) PTC models (ET100 and ET150) with an operating temperature of 500 °C and a concentration ratio of 82:1. They also studied a wind channel and Finite Element Analysis (FEA) to study collector structure geometry. Their findings showed an annual output increase of 20% [82]. In addition, they assessed the impact of utilizing different types of sun tracking systems on the (voltage–current) characteristics and electrical power for flat-plate photovoltaic by comparing the four types of electromechanical sun tracking systems: axis vertical, axis north–south, axis east–west, and two axes. The volt–ampere characteristics on the tracking surfaces were more than that on a fixed surface [83]. Bakos developed a sun tracking system with two axes for PTC, and the tracking system was easy to install and operate with low maintenance requirements and cost. The thermal efficiency of PTC using sun tracking improved by 46.46% more than the fixed one [84]. Jeter considered several parameters, such as concentrated flux density, concentration ratio, and optical efficiency to achieve performance analysis. Optical efficiency can be enhanced with absorption, reflection, and transmission properties of the collector [12]. Arasu and Sornakumar improved cost and thermal efficiency by developing a fiber-reinforced plastic-based solar PTC with an electronically-controlled tracking system [85]. Bellos et al. stated that the two parameters, namely, absorber geometry and working fluid type became increasingly effective in thermal efficiency by enhancing the heat transfer coefficient between the working fluid and receiver tube. Therefore, they examined several types of working fluids, such as pressurized water, thermal oil, and thermal oil with nanoparticles. They reported that the geometrical enhancement increased efficiency by 4.55%, whereas the use of nanofluids increased thermal efficiency by 4.25% [86]. Nanofluids are generally materials in a solid-liquid composite and consists of solid nanoparticles suspended in liquid with a size of 1–100 nm [87]. Kaloudis et al. presented an simulation using nanofluid type Syltherm 800/Al2O3 as a working fluid. Results showed increased collector thermal effyciency [88]. Bakos et al. developed a simulation design to improve the receiver tube heat transfer rate and showed that the

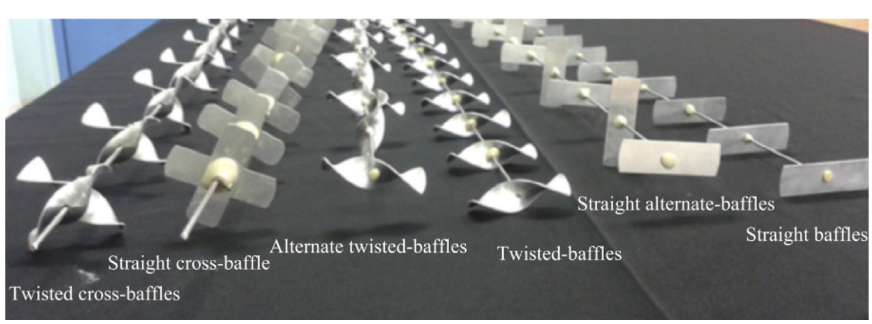


**Fig. 8.** Photograph of twisted cross-baffles, straight cross-baffles, twisted-baffles, alternate twisted-baffles straight alternate-baffles and straight baffles [64].

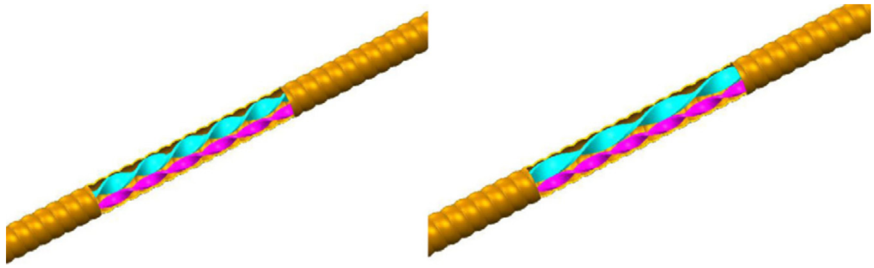

**Fig. 9.** Spiral grooved tube and twisted tapes [66].

collector thermal efficiency depends on the pipe diameter, PTC active area, fluid heat flux, and solar radiation intensity [89]. You et al. analyzed heat transfer and flow by employing a finite difference method in comparison with the experimental result. Subsequently, the result demonstrated improved efficiency with a temperature range of above 300 °C [90].

Silva et al. performed a parametric analysis which showed that the collector efficiency was affected by design properties improvement such as absorber absorption and emittance [91]. Lobón et al. used the computational fluid dynamic (CFD) package STAR-CCM + to improve steam generation in PTC with utilize water as the working fluid and for comparison with the experimental results. The comparison showed suitable agreement and better thermal efficiency with a minimal variations in pressure losses and temperature of about 0.02 MPa and 3 °C, respectively [92]. De Risi et al. made an innovative PTC with transparent receiver tube, transparent envelope cover, and gas-based nanofluids as working fluid. A nanofluid consists of nanoparticles mixture and nitrogen, the nitrogen use to avoid metal particles oxidation. The nanofluid is absorbed by the heat flow focused on the tube. Simulation results showed that the receiver's thermal efficiency and nanofluid temperature are 62.5% and 650 °C, respectively [93].

A receiver tube is generally made from metal tube. In addition, the receiver tube should be constructed from metal with high solar absorption ability and low emittance coefficient to achieve minimum heat loss and maximum thermal efficiency [77]. Hachicha et al. studied the improvement of thermal efficiency by analyzing the aerodynamic aspect of the PTC and its heat transfer coefficient around the collector [94,95]. Cheng et al. carried out a numerical study to enhance thermal efficiency and reduce thermal loss by 2.23–13.62% using unilateral milt-longitudinal vortexes (UMLVE) (artificial therml oil), wherein UMLVEs were only found on the absorber tube with focused solar radiation. The study examined the heat transfer effects of fluid, Reynolds number, geometric parameters, and incident solar radiation [96].

Yaghoubi et al. presented a numerical and experimental analysis of heat loss in the receiver tube, demonstrating that heat loss in lost vacuum tube is approximately 40% more than that in the vacuum jacket tube which causes a 3–5% reduction in the efficiency of the collector [97]. Numerous researchers have focused on numerical analysis and measured the absorber's thermal efficiency with the experimental result [29,98,99]. According to previous reviews, CFD, FEM, and parametric optimization methodology were used to validate the experimental results. These methods may be utilized for the research and development of solar energy by enhancing its thermal efficiency.

## 6. PTC applications

Currently, fossil fuel is costly and increases air pollution; therefore, solar energy demand rapidly and significantly increased for various industrial purposes. Solar PTC applications are summarized as follows:

### 6.1. Solar energy for desalination process

Desalination process is the procedure of converting brackish water into drinking water. One of the common methods of desalination is the Reverse Osmosis (RO) method [100]. Nafey and Sharaf studied this process by using different heat transfer fluids (Toluene and water, hexane and butane) on a combined solar organic Rankin cycle with RO. Results showed that at superheated temperature, the Toluene and water as working fluids demonstrated superior performance compared with that of hexane and butane [101]. Jafari et al. designed and manufactured a new desalination system that purified water using a PTC with a copper tube as the absorber tube covered by a black dying evacuated glass tube and the space between the copper tube and the dying glass fulled with an aluminum foil with high thermal conductivity, which is used to conduct heat from glass tube to copper heat pipe. Inside the copper tube, ethanol evaporates because of the high rate of heat absorption and travels up the condenser which is connected to the absorber tube. The condenser converts brackish water into vapor as a result of the high temperature of ethanol. The new desalination technique efficiency and production can increase up to 65.2% and 0.933 $kg/m^2h$, respectively [102]. Sharaf et al. conducted several studies on the combined multi-effect distillation desalination process with solar organic cycle. Results showed a high gain ratio and the need of a system for a small solar field [103].

### 6.2. Solar PTC as air heating system

The solar air heating system (SAHS) has no negative impact on the environment because it is sourced from green energy. The SAHS is used to heat buildings and for drying applications in the marine foodstuff, agriculture, and textiles industries. SAHS can be categorized into three types, namely active, passive, and hybrid systems, with or without storage systems [104]. In addition, two methods exist for achieving a storage system called rock bed and Phase Change Materials (PCM). Tyagi et al. explained and discussed the type and specifications of air heating system with Phase Change Material, showing that the sensible heat storage system is less accurate than the latent heat storage system [105]. Many researchers have shown that the basis of a thermal energy storage system is use PCM in solar air heater, which stores energy by changing the phase from solid to liquid. Phase Change Materials treats energy leak at night or on cloudy days. Paraffin, non-paraffin, hydrated salts (calcium chloride hexahydrate), and fatty acids are common thermal energy storage materials [106–114]. Other researchers have conducted a simulation design to identify the physical properties of energy storage PCM [115,116]. Hammou and Lacroix validated experimental data with simulation results and suggested a novel hybrid energy storage system for reducing electric overload during peak period by using FCM for the storage of solar energy for use at night or on cloudy days in two separate studies. Electric energy consumption is reduced by 90% at high demand period, whereas household consumption decreased by 32%. Thus, the consumption during January may be reduced by as much as 30% [117,118], making the use of solar energy in air heating systems for thermal storage a suitable choice.

### 6.3. Solar energy in refrigeration system

In hot and humid regions, humidity is removed using conventional air conditioners (A/C), which involves a considerable load on the air conditioning device. Solar energy is used in refrigeration and air conditioning systems, whereas in air conditioning, the air temperature is reduced below dew point through dehumidification and then by reheating the air for the remainder of the required comfort level. Numerous studies have focused on solar thermal cooling technologies, and their general efficiencies are not at the design level and lower than that of the vapor compression cycles. Therefore, enhancing the efficiency of solar thermal A/C technologies should be continuously studied [119]. Al-Alili et al. used desiccant assisted air conditioning (hybrid A/C) to reduce the load on the A/C device. The design was investigated experimentally by studying the influence of the process of the air stream's humidity and temperature, and the impact of the ventilation rate on the performance of the hybrid A/C. Experimental results showed that the hybrid A/C is more effective than conventional air conditioners in comfort regions [120]. Al-Alili et al. presented the solar A/C utilizing photovoltaic thermal collectors. Findings proved that sensible and latent loads are very effective in meeting the temperature and humidity requirements of buildings in hot and moist weather. Furthermore, testing throughout the year showed the system's overall performance coefficient as higher than other types of solar A/C [121]. El Fadar et al. presented a refrigeration system with an advanced solar absorption PTC for evaporating working fluid. The refrigeration cycle, consisting of a condenser, an evaporator, refrigerant valves, a cylindrical absorber, and a solar PTC, is more efficient than conventional refrigeration systems [122].

The researchers conducted experimental analysis on solar collector using solar energy for heating and electrical purposes and found improved efficiency [123–125]. Several researchers have clarified the industrial applications of solar energy systems and shown that the steady thermal efficiency and temperature level should be 60–80 °C [126,127].

### 6.4. Solar PTC in power plants

In recent decades, many countries have used solar powered PTC in heating processes to assist electrical power plants by converting solar to thermal energy utilizing PTC in power plants, which is common in the world due to high temperature and concentration ratio. Operating a power plant requires high pressure steam which can be obtained from solar PTC at 18 bar pressure [128]. Hachicha et al. employed a finite volume method for the receiver tube of PTC to achieve numerical heat transfer design to enhance the output performance of the power plant [129]. Larrain et al. developed a thermodynamical design to estimate the support section necessary in a (100 MW) hybrid-solar-fossil-parabolic trough power plant [130]. Bishoyi and Sudhakar evaluated the six-hour thermal energy storage of A (100 MW) PTC solar thermal power plant in terms of thermal performance and design based on the System Advisor Model [131]. Nation et al. presented the mathematical modeling of the solar PTC receiver tube with a novel Electrical Energy Storage. Results were highly consistent with established PTC under adiabatic conditions [132]. Qiu et al. presented a numerical design to address the complex energy transfer in a PTC through the combination of finite volume method and Monte Carlo ray tracing. They used supercritical CO2 (s-CO2) as working fluid. Under the typical conditions for Rankine and Brayton cycles, PTC can achieve a collector efficiency of 81.93–84.17% and 18.78–84.17%, respectively. [133]. Price employed simulation analysis on solar PTC power plant to improve annual power generation [134]. Researchers have suggested that solar electric generation systems with water should be used as working fluid instead of using artificial oil in PTC in future direct steam generations. However, current power plants operate by using artificial oil (thermal oil or molten salts made of nitrates) as PTC working fluid for the transfer of thermal energy to a Rankine cycle turbine by heat exchanger. Result showed a reduction of electrical cost by 10% with high system efficiency and improved solar power plants [135–138]. Other researchers have also used artificial oil as the working fluid in solar power plants with PTC, and the findings indicated a generation of 400 °C outlet temperature [18]. Muñoz and Abánades utilized CFD tools to design the PTC for studying the influence of using internal finned absorber tube. Results showed improvement in performance of PTC power plant using the new technique [139]. Farooq and Raja described the optimized design of PTC power plant receiver tube by using copper and aluminum coatings by materials with minimum thermal emittance and maximum solar absorption to enhance power plant output [140]. De Jong et al. examined the effectiveness of analyzing wind energy and solar power for supplying electricity to the grid during periods of peak demand. Findings demonstrated that renewable energy can help support the demand of electricity grid more effectively than fossil fuel power plants [141].

### 6.5. Solar PTC for industrial purposes

The utilization of solar energy decreases the consumption of available electricity as a result of industrial processes such as cooking, drying, cleaning or degreasing, and Pasteurization purification. Most industrial processes require temperature of less than 300 °C [142]. Solar PTC can provide the heat required for industrial processes due to its ability to produce temperature higher than 300 °C [67,143,144].

## 7. Conclusion

The current review focused on energy crisis that improved the innovative study especially of renewable energy. Solar energy is the ideal strategy to meet the present increasing power demand, which is projected to further increase in the future. This paper also presents a review of PTC models throughout the history of technology, brief applications, commercial availability, mentioning their main features, manufactures, and their development.

Solar collectors contribute to more improvement in thermal applications. The PTC can produced up to 400 °C temperature of heat. Various studies have shown the following:

- Receiver geometrical analysis with numerous absorber modifications is conducted in the PTC system and comprehensive heat transfer by examining absorbed and glass envelopes. Changes in receiver geometry indicate the perfect enhancement of thermal efficiency.
- The analysis of the structure and performance of PTC showed that essential parameters, such as working fluid heat transfer coefficient, reflection, optical efficiency, adsorption, heat flux, transmission, collector length, and absorber diameter, should be optimized to deal with environmental conditions.
- The PTC Thermal analysis indicates that a thermal efficiency enhancement can be achieved by optimizing essential affecting parameters, such as differing working fluid, absorber materials, and absorber coatings.
- The use of phase change material as a thermal storage system on PTC solar power creates an important pathway for a wide range of thermal applications in future. The PCM from solid to liquid assets saves abundant thermal energy that can be utilized during cloudy days and at night time.
- This paper also emphasized the applications of PTC in the desalination process and industrial purposes, as well as air heating and refrigeration systems.

In general, the solar PTC advanced research has indicated that using PTC is ideal in collecting maximum solar energy for various applications.

## Acknowledgements

The financial support by Putra grant for post graduate (IPS) is highly acknowledged. Also, the Journals that organized under Elsevier (Solar Energy, Applied Energy, Energy, Renewable Energy, Experimental Thermal and Fluid Science, International Journal of Heat and Mass Transfer, and Applied Thermal Engineering) which gave permission to re-use some figures are duly acknowledged.

## References

[1] García-Cortés S, Bello-García A, Ordóñez C. Estimating intercept factor of a parabolic solar trough collector with new supporting structure using off-the-shelf photogrammetric equipment. Appl Energy 2012;92:815–21. http://dx.doi.org/10.1016/j.apenergy.2011.08.032.

[2] Rajaseenivasan T, Elango T, Kalidasa Murugavel K. Comparative study of double basin and single basin solar stills. Desalination 2013;309:27–31. http://dx.doi.org/10.1016/j.desal.2012.09.014.

[3] Lüpfert E, Geyer M, Zentrum D, Schiel W, Esteban A, Osuna R, et al. Eurotrough design issues and prototype testing At Psa. Sol Forum 2001:1–5.

[4] Pytilinski JT. Solar energy installations for pumping irrigation water. Sol Energy 1978;21:255–62. http://dx.doi.org/10.1016/0038-092X(78)90001-4.

[5] Spencer LC. A comprehensive review of small solar-powered heat engines: part I. A history of solar-powered devices up to 1950. Sol Energy 1989;43:191–6. http://dx.doi.org/10.1016/0038-092X(89)90019-4.

[6] Shaner WW, Duff WS. Solar thermal electric power systems: comparison of line-focus collectors. Sol Energy 1979;22:49–61.

[7] Fernández-García A, Zarza E, Valenzuela L, Pérez M. Parabolic-trough solar collectors and their applications. Renew Sustain Energy Rev 2010;14:1695–721. http://dx.doi.org/10.1016/j.rser.2010.03.012.

[8] Gong G, Huang X, Wang J, Hao M. An optimized model and test of the China's first high temperature parabolic trough solar receiver. Sol Energy 2010;84:2230–45. http://dx.doi.org/10.1016/j.solener.2010.08.003.

[9] Eskin N. Transient performance analysis of cylindrical parabolic concentrating collectors and comparison with experimental results. Energy Convers Manag 1999;40:175–91. http://dx.doi.org/10.1016/S0196-8904(98)00035-1.

[10] Naeeni N, Yaghoubi M. Analysis of wind flow around a parabolic collector (2) heat transfer from receiver tube. Renew Energy 2007;32:1259–72. http://dx.doi.org/10.1016/j.renene.2006.06.005.

[11] Burkhard DG, Shealy DL, Sexl RU. Specular reflection of heat radiation from an arbitrary reflector surface to an arbitrary receiver surface. Int J Heat Mass Transf 1973;16:271–80. http://dx.doi.org/10.1016/0017-9310(73)90056-2.

[12] Jeter SM. Analytical determination of the optical performance of practical parabolic trough collectors from design data. Sol Energy 1987;39:11–21. http://dx.doi.org/10.1016/S0038-092X(87)80047-6.

[13] Eck M, Feldhoff JF, Uhlig R. Thermal Modelling and Simulation of Parabolic Trough Receiver Tubes. ASME 2010 4th Int Conf Energy Sustain Vol 2 2010:659–66. 〈http://dx.doi.org/10.1115/ES2010-90402〉.

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

[15] Collares M, Gordon JM, Rabl A, Winston R. High concentration two-stage optics for parabolic trough solar collector with tubular absorber and large rim angle. Sol Energy 1991;47:457–66.

[16] Canavarro D, Chaves J, Collares-Pereira M. New second-stage concentrators (XX SMS) for parabolic primaries; Comparison with conventional parabolic trough concentrators. Sol Energy 2013;92:98–105. http://dx.doi.org/10.1016/j.solener.2013.02.011.

[17] Menbari A, Alemrajabi AA, Rezaei A. Experimental investigation of thermal performance for direct absorption solar parabolic trough collector (DASPTC) based on binary nanofluids. Exp Therm Fluid Sci 2017;80:218–27. http://dx.doi.org/10.1016/j.expthermflusci.2016.08.023.

[18] Price H, Lüpfert E, Kearney D, Zarza E, Cohen G, Gee R, et al. Advances in parabolic trough solar power technology. J Sol Energy Eng 2002;124:109. http://dx.doi.org/10.1115/1.1467922.

[19] Sup BA, Zainudin MF, ZanariahShamsirAli T, Bakar RA, Ming GL. Effect of rim angle to the flux distribution diameter in solar parabolic dish collector. Energy Proc 2015;68:45–52. http://dx.doi.org/10.1016/j.egypro.2015.03.231.

[20] Kasaeian A, Daviran S, Azarian RD, Rashidi A. Performance evaluation and nanofluid using capability study of a solar parabolic trough collector. Energy Convers Manag 2015;89:368–75. http://dx.doi.org/10.1016/j.enconman.2014.09.056.

[21] Rabl A. Comparison of solar concentrators. Sol Energy 1976;18:93–111. http://dx.doi.org/10.1016/0038-092X(76)90043-8.

[22] Shankar Ganesh N, Srinivas T. Design and modeling of low temperature solar thermal power station. Appl Energy 2012;91:180–6. http://dx.doi.org/10.1016/j.apenergy.2011.09.021.

[23] Valan Arasu A, Sornakumar T. Design, manufacture and testing of fiberglass reinforced parabola trough for parabolic trough solar collectors. Sol Energy 2007;81:1273–9. http://dx.doi.org/10.1016/j.solener.2007.01.005.

[24] Gaul H, Rabl A. Incidence-angle modifier and average optical efficiency of parabolic trough collectors. J Sol Energy Eng 1980;102:16–21.

[25] Güven HM, Bannerot RB. Determination of error tolerances for the optical design of parabolic troughs for developing countries. Sol Energy 1986;36:535–50. http://dx.doi.org/10.1016/0038-092X(86)90018-6.

[26] Arasu AV, Sornakumar T. Performance Characteristics of Parabolic Trough Solar Collector System for. Int Energy J 2006;7:137–46.

[27] De Oliveira SAM, Gomes PEN, Torrezani L, Lucas EO, Da Cruz Pereira GM. Heat transfer analysis and modeling of a parabolic trough solar collector: an analysis. Energy Proc 2014;57:401–10. http://dx.doi.org/10.1016/j.egypro.2014.10.193.

[28] Sun J, Liu Q, Hong H. Numerical study of parabolic-trough direct steam generation loop in recirculation mode: characteristics, performance and general operation strategy. Energy Convers Manag 2015;96:287–302. http://dx.doi.org/10.1016/j.enconman.2015.02.080.

[29] Kalogirou SA. A detailed thermal model of a parabolic trough collector receiver. Energy 2012;48:298–306. http://dx.doi.org/10.1016/j.energy.2012.06.023.

[30] Lu J, Ding J, Yang J, Yang X. Nonuniform heat transfer model and performance of parabolic trough solar receiver. Energy 2013;59:666–75. http://dx.doi.org/10.1016/j.energy.2013.07.052.

[31] Cheng ZD, He YL, Qiu Y. A detailed nonuniform thermal model of a parabolic trough solar receiver with two halves and two inactive ends. Renew Energy 2015;74:139–47. http://dx.doi.org/10.1016/j.renene.2014.07.060.

[32] Salgado Conrado L, Rodriguez-Pulido A, Calderón G. Thermal performance of parabolic trough solar collectors. Renew Sustain Energy Rev 2017;67:1345–59. http://dx.doi.org/10.1016/j.rser.2016.09.071.

[33] Wu Z, Li S, Yuan G, Lei D, Wang Z. Three-dimensional numerical study of heat transfer characteristics of parabolic trough receiver. Appl Energy 2014;113:902–11. http://dx.doi.org/10.1016/j.apenergy.2013.07.050.

[34] Yilmaz IH, Söylemez MS. Thermo-mathematical modeling of parabolic trough collector. Energy Convers Manag 2014;88:768–84. http://dx.doi.org/10.1016/j.enconman.2014.09.031.

[35] Zhang L, Yu Z, Fan L, Wang W, Chen H, Hu Y, et al. An experimental investigation of the heat losses of a U-type solar heat pipe receiver of a parabolic trough collector-based natural circulation steam generation system. Renew Energy 2013;57:262–8. http://dx.doi.org/10.1016/j.renene.2013.01.029.

[36] Nolte HC, Bello-Ochende T, Meyer JP. Second law analysis and optimization of a parabolic trough receiver tube for direct steam generation. Heat Mass Transf Stoff 2015;51:875–87. http://dx.doi.org/10.1007/s00231-014-1465-3.

[37] Wu Z, Lei D, Yuan G, Shao J, Zhang Y, Wang Z. Structural reliability analysis of parabolic trough receivers. Appl Energy 2014;123:232–41. http://dx.doi.org/10.1016/j.apenergy.2014.02.068.

[38] Zou B, Dong J, Yao Y, Jiang Y. An experimental investigation on a small-sized parabolic trough solar collector for water heating in cold areas. Appl Energy 2016;163:396–407. http://dx.doi.org/10.1016/j.apenergy.2015.10.186.

[39] Fuqiang W, Zhexiang T, Xiangtao G, Jianyu T, Huaizhi H, Bingxi L. Heat transfer performance enhancement and thermal strain restrain of tube receiver for parabolic trough solar collector by using asymmetric outward convex corrugated tube. Energy 2016;114:275–92. http://dx.doi.org/10.1016/j.energy.2016.08.013.

[40] Hegazy AS. Thermal performance of a parabolic trough collector with a longitudinal externally finned absorber. Heat Mass Transf 1995;31:95–103. http://dx.doi.org/10.1007/BF02537427.

[41] Jaramillo O a, Borunda M, Velazquez-Lucho KM, Robles M. Parabolic trough solar collector for low enthalpy processes: an analysis of the efficiency enhancement by using twisted tape inserts. Renew Energy 2016;93:125–41. http://dx.doi.org/10.1016/j.renene.2016.02.046.

[42] Jafar KS, Sivaraman B. Thermal performance of solar parabolic trough collector using nanofluids and the absorber with nail twisted tapes inserts. Int Energy J 2014;14:189–98.

[43] Ananth J, Jaisankar S. Experimental studies on heat transfer and friction factor characteristics of thermosyphon solar water heating system fitted with regularly spaced twisted tape with rod and spacer. Energy Convers Manag 2013;73:207–13. http://dx.doi.org/10.1016/j.enconman.2013.04.022.

[44] Jaisankar S, Radhakrishnan TK, Sheeba KN. Experimental studies on heat transfer and thermal performance characteristics of thermosyphon solar water heating system with helical and Left-Right twisted tapes. Energy Convers Manag 2011;52:2048–55. http://dx.doi.org/10.1016/j.enconman.2010.11.024.

[45] Jaisankar S, Radhakrishnan TK, Sheeba KN. Studies on heat transfer and friction factor characteristics of thermosyphon solar water heating system with helical twisted tapes. Energy 2009;34:1054–64. http://dx.doi.org/10.1016/j.energy.2009.03.015.

[46] Jaisankar S, Radhakrishnan TK, Sheeba KN. Experimental studies on heat transfer and friction factor characteristics of forced circulation solar water heater system fitted with left-right twisted tapes. Int Energy J 2008;9:199–206. http://dx.doi.org/10.1016/j.solener.2009.07.006.

[47] Jaisankar S, Radhakrishnan TK, Sheeba KN. Experimental studies on heat transfer and friction factor characteristics of thermosyphon solar water heater system fitted with spacer at the trailing edge of twisted tapes. Appl Therm Eng 2009;29:1224–31. http://dx.doi.org/10.1016/j.applthermaleng.2008.06.009.

[48] Jaisankar S, Radhakrishnan TK, Sheeba KN, Suresh S. Experimental investigation of heat transfer and friction factor characteristics of thermosyphon solar water heater system fitted with spacer at the trailing edge of Left-Right twisted tapes. Energy Convers Manag 2009;50:2638–49. http://dx.doi.org/10.1016/j.enconman.2009.06.019.

[49] Saravanan A, Senthilkumaar JS, Jaisankar S. Performance assessment in V-trough solar water heater fitted with square and V-cut twisted tape inserts. Appl Therm Eng 2016;102:476–86. http://dx.doi.org/10.1016/j.applthermaleng.2016.03.088.

[50] Kumar A, Prasad B. Investigation of twisted tape inserted solar water heaters—heat transfer, friction factor and thermal performance results. Renew Energy

2000;19:379–98. http://dx.doi.org/10.1016/S0960-1481(99)00061-0.
[51] Yao K, Li T, Tao H, Wei J, Feng K. Performance evaluation of all-glass evacuated tube solar water heater with twist tape inserts using CFD. Energy Procedia 2015;70:332–9. http://dx.doi.org/10.1016/j.egypro.2015.02.131.
[52] Piriyarungrod N, Eiamsa-ard S, Thianpong C, Pimsarn M, Nanan K. Heat transfer enhancement by tapered twisted tape inserts. Chem Eng Process Process Intensif 2015;96:62–71. http://dx.doi.org/10.1016/j.cep.2015.08.002.
[53] Ghadirijafarbeigloo S, Zamzamian AH, Yaghoubi M. 3-D numerical simulation of heat transfer and turbulent flow in a receiver tube of solar parabolic trough concentrator with louvered twisted-tape inserts. Energy Proc 2013;49:373–80. http://dx.doi.org/10.1016/j.egypro.2014.03.040.
[54] Eiamsa-ard S, Thianpong C, Eiamsa-ard P. Turbulent heat transfer enhancement by counter/co-swirling flow in a tube fitted with twin twisted tapes. Exp Therm Fluid Sci 2010;34:53–62. http://dx.doi.org/10.1016/j.expthermflusci.2009.09.002.
[55] Mwesigye A, Bello-Ochende T, Meyer JP. Multi-objective and thermodynamic optimisation of a parabolic trough receiver with perforated plate inserts. Appl Therm Eng 2015;77:42–56. http://dx.doi.org/10.1016/j.applthermaleng.2014.12.018.
[56] Mwesigye A, Bello-Ochende T, Meyer JP. Heat transfer and thermodynamic performance of a parabolic trough receiver with centrally placed perforated plate inserts. Appl Energy 2014;136:989–1003. http://dx.doi.org/10.1016/j.apenergy.2014.03.037.
[57] Zhang L, Hua M, Lu H, Fan L, Mei R. Effect of receiver diameter ratio on thermal performance of natural circulation steam generation system as applied to parabolic trough collector using water as working fluid. Int J Heat Mass Transf 2016;92:1191–200. http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.09.075.
[58] Wang F, Tan J, Ma L, Wang C. Effects of glass cover on heat flux distribution for tube receiver with parabolic trough collector system. Energy Convers Manag 2015;90:47–52. http://dx.doi.org/10.1016/j.enconman.2014.11.004.
[59] Diwan K, Soni MS. Heat transfer enhancement in absorber tube of parabolic trough concentrators using wire- coils inserts heat transfer enhancement in absorber tube of parabolic trough concentrators using wire-coils inserts. Univ J Mech Eng 2015;3:107–12. http://dx.doi.org/10.13189/ujme.2015.030305.
[60] Martín RH, Pérez-García J, García A, García-Soto FJ, López-Galiana E. Simulation of an enhanced flat-plate solar liquid collector with wire-coil insert devices. Sol Energy 2011;85:455–69. http://dx.doi.org/10.1016/j.solener.2010.12.013.
[61] García A, Vicente PG, Viedma A, Mecanismo H. Experimental Investigation on Heat Transfer and Frictional Characteristics; 2005.
[62] Choudhari PSS, PTS G. Experimental studies on effect of coil wire insert on heat transfer enhancement and friction factor of double pipe heat exchanger. Int J Comput Eng Res 2013;3:32–9.
[63] Amina B, Miloud A, Samir L, Abdelylah B, Solano JP. Heat transfer enhancement in a parabolic trough solar receiver using longitudinal fins and nanofluids. J Therm Sci 2016;25:410–7. http://dx.doi.org/10.1007/s11630-016-0878-3.
[64] Nanan K, Thianpong C, Pimsarn M, Chuwattanakul V, Eiamsa-ard S. Flow and thermal mechanisms in a heat exchanger tube inserted with twisted cross-baffle turbulators. Appl Therm Eng 2017;114:130–47. http://dx.doi.org/10.1016/j.applthermaleng.2016.11.153.
[65] Waghole DR, Warkhedkar RM, Kulkarni VS, Shrivastva RK. Experimental investigations on heat transfer and friction factor of silver nanofliud in absorber/receiver of parabolic trough collector with twisted tape inserts. Energy Proc 2014;45:558–67. http://dx.doi.org/10.1016/j.egypro.2014.01.060.
[66] Hong Y, Du J, Wang S. Experimental heat transfer and flow characteristics in a spiral grooved tube with overlapped large/small twin twisted tapes. Int J Heat Mass Transf 2017;106:1178–90. http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.10.098.
[67] Shahin MS, Orhan MF, Uygul F. Thermodynamic analysis of parabolic trough and heliostat field solar collectors integrated with a Rankine cycle for cogeneration of electricity and heat. Sol Energy 2016;136:183–96. http://dx.doi.org/10.1016/j.solener.2016.06.057.
[68] Padilla RV, Demirkaya G, Goswami DY, Stefanakos E, Rahman MM. Heat transfer analysis of parabolic trough solar receiver. Appl Energy 2011;88:5097–110. http://dx.doi.org/10.1016/j.apenergy.2011.07.012.
[69] Paetzold J, Cochard S, Fletcher DF, Vassallo A. Wind engineering analysis of parabolic trough collectors to optimise wind loads and heat loss. Energy Proc 2015;69:168–77. http://dx.doi.org/10.1016/j.egypro.2015.03.020.
[70] Paetzold J, Cochard S, Vassallo A, Fletcher DF. Wind engineering analysis of parabolic trough solar collectors: the effects of varying the trough depth. J Wind Eng Ind Aerodyn 2014;135:118–28. http://dx.doi.org/10.1016/j.jweia.2014.10.017.
[71] Andre M, Mier-Torrecilla M, Wüchner R. Numerical simulation of wind loads on a parabolic trough solar collector using lattice Boltzmann and finite element methods. J Wind Eng Ind Aerodyn 2015;146:185–94. http://dx.doi.org/10.1016/j.jweia.2015.08.010.
[72] Naeeni N, Yaghoubi M. Analysis of wind flow around a parabolic collector (1) fluid flow. Renew Energy 2007;32:1898–916. http://dx.doi.org/10.1016/j.renene.2006.10.004.
[73] Hosoya N, Peterka J a, Gee RC, Kearney D. Wind Tunnel Tests of Parabolic Trough Solar Collectors; 2008:133.
[74] Zhang L, Yang MC, Zhu YZ, Chen HJ. Numerical study and optimization of mirror gap effect on wind load on parabolic trough solar collectors. Energy Proc 2015;69:233–41. http://dx.doi.org/10.1016/j.egypro.2015.03.027.
[75] Price H, Forristall R, Wendelin T, Lewandowski a, Moss T. Field Survey of Parabolic Trough Receiver Thermal Performance Preprint. Proc ISEC2006 ASME Int Sol Energy Conf July 8-13, 2006, Denver, Color USA 2006:1–11. ⟨http://dx.doi.org/10.1115/ISEC2006-99167⟩.
[76] Edenburn MW. Performance analysis of a cylindrical parabolic focusing collector and comparison with experimental results. Sol Energy 1976;18:437–44. http://dx.doi.org/10.1016/0038-092X(76)90010-4.
[77] Kalogirou SA. Solar thermal collectors and applications. vol. 30; 2004. ⟨http://dx.doi.org/10.1016/j.pecs.2004.02.001⟩.
[78] Omer SA, Infield DG. Design and thermal analysis of a two stage solar concentrator for combined heat and thermoelectric power generation. Energy Convers Manag 2000;41:737–56. http://dx.doi.org/10.1016/S0196-8904(99)00134-X.
[79] Gang P, Jing L, Jie J. Design and analysis of a novel low-temperature solar thermal electric system with two-stage collectors and heat storage units. Renew Energy 2011;36:2324–33. http://dx.doi.org/10.1016/j.renene.2011.02.008.
[80] Venegas-Reyes E, Jaramillo OA, Castrejón-García R, Aguilar JO, Sosa-Montemayor F. Design, construction, and testing of a parabolic trough solar concentrator for hot water and low enthalpy steam generation. J Renew Sustain Energy 2012;4:053103. http://dx.doi.org/10.1063/1.4751461.
[81] Jaramillo OA, Venegas-Reyes E, Aguilar JO, Castrejón-García R, Sosa-Montemayor F. Parabolic trough concentrators for low enthalpy processes. Renew Energy 2013;60:529–39. http://dx.doi.org/10.1016/j.renene.2013.04.019.
[82] Geyer M, Lüpfert E. E URO T rough - parabolic trough collector developed for cost efficient solar power generation. Transportation 2002:1–7.
[83] Abdallah S. The effect of using sun tracking systems on the voltage-current characteristics and power generation of flat plate photovoltaics. Energy Convers Manag 2004;45:1671–9. http://dx.doi.org/10.1016/j.enconman.2003.10.006.
[84] Bakos GC. Design and construction of a two-axis Sun tracking system for parabolic trough collector (PTC) efficiency improvement. Renew Energy 2006;31:2411–21. http://dx.doi.org/10.1016/j.renene.2005.11.008.
[85] Valan Arasu A, Sornakumar T, Arasu AV. Life cycle cost analysis of new FRP based solar parabolic trough collector hot water generation system. J Zhejiang Univ Sci A 2008;9:416–22. http://dx.doi.org/10.1631/jzus.A072134.
[86] Bellos E, Tzivanidis C, Antonopoulos KA, Gkinis G. Thermal enhancement of solar parabolic trough collectors by using nanofluids and converging-diverging absorber tube. Renew Energy 2016;94:213–22. http://dx.doi.org/10.1016/j.renene.2016.03.062.
[87] Wu S, Zhu D, Li X, Li H, Lei J. Thermal energy storage behavior of Al2O3-H2O nanofluids. Thermochim Acta 2009;483:73–7. http://dx.doi.org/10.1016/j.tca.2008.11.006.
[88] Kaloudis E, Papanicolaou E, Belessiotis V. Numerical simulations of a parabolic trough solar collector with nanofluid using a two-phase model. Renew Energy 2016;97:218–29. http://dx.doi.org/10.1016/j.renene.2016.05.046.
[89] Bakos GC, Ioannidis I, Tsagas NF, Seftelis I. Design, optimisation and conversion-efficiency determination of a line-focus parabolic-trough solar-collector (PTC). Appl Energy 2000;68:43–50. http://dx.doi.org/10.1016/S0306-2619(00)00034-9.
[90] You C, Zhang W, Yin Z. Modeling of fluid flow and heat transfer in a trough solar collector. Appl Therm Eng 2013;54:247–94. http://dx.doi.org/10.1016/j.applthermaleng.2013.01.046.
[91] Silva R, Pérez M, Fernández-Garcia A. Modeling and co-simulation of a parabolic trough solar plant for industrial process heat. Appl Energy 2013;106:287–300. http://dx.doi.org/10.1016/j.apenergy.2013.01.069.
[92] Lobón DH, Baglietto E, Valenzuela L, Zarza E. Modeling direct steam generation in solar collectors with multiphase CFD. Appl Energy 2014;113:1338–48. http://dx.doi.org/10.1016/j.apenergy.2013.08.046.
[93] De Risi A, Milanese M, Laforgia D. Modelling and optimization of transparent parabolic trough collector based on gas-phase nanofluids. Renew Energy 2013;58:134–9. http://dx.doi.org/10.1016/j.renene.2013.03.014.
[94] Hachicha AA, Rodríguez I, Oliva A. Wind speed effect on the flow field and heat transfer around a parabolic trough solar collector. Appl Energy 2014;130:200–11. http://dx.doi.org/10.1016/j.apenergy.2014.05.037.
[95] Hachicha AA, Rodríguez I, Castro J, Oliva A. Numerical simulation of wind flow around a parabolic trough solar collector. Appl Energy 2013;107:426–37. http://dx.doi.org/10.1016/j.apenergy.2013.02.014.
[96] Cheng ZD, He YL, Cui FQ. Numerical study of heat transfer enhancement by unilateral longitudinal vortex generators inside parabolic trough solar receivers. Int J Heat Mass Transf 2012;55:5631–41. http://dx.doi.org/10.1016/j.ijheatmasstransfer.2012.05.057.
[97] Yaghoubi M, Ahmadi F, Bandehee M. Analysis of heat losses of absorber tubes of parabolic through collector of Shiraz (Iran) solar power plant. J Clean Energy Technol 2013;1:33–7. http://dx.doi.org/10.7763/JOCET.2013.V1.8.
[98] Ravi Kumar K, Reddy KS. Thermal analysis of solar parabolic trough with porous disc receiver. Appl Energy 2009;86:1804–12. http://dx.doi.org/10.1016/j.apenergy.2008.11.007.
[99] García-Valladares O, Velázquez N. Numerical simulation of parabolic trough solar collector: improvement using counter flow concentric circular heat exchangers. Int J Heat Mass Transf 2009;52:597–609. http://dx.doi.org/10.1016/j.ijheatmasstransfer.2008.08.004.
[100] Bhattacharyya A. Solar stills for desalination of water in rural households. Int J Environ Sustain 2013;2:21–30.
[101] Nafey AS, Sharaf MA. Combined solar organic Rankine cycle with reverse osmosis desalination process: energy, exergy, and cost evaluations. Renew Energy 2010;35:2571–80. http://dx.doi.org/10.1016/j.renene.2010.03.034.
[102] Jafari MH, Mamouri SJ, Shafii MB, Hakim Sima A. A new desalination system using a combination of heat pipe, evacuated tube and parabolic through collector. Energy Convers Manag 2015;99:141–50. http://dx.doi.org/10.1016/j.enconman.2015.04.028.
[103] Sharaf MA, Nafey AS, García-Rodríguez L. Exergy and thermo-economic analyses of a combined solar organic cycle with multi effect distillation (MED) desalination process. Desalination 2011;272:135–47. http://dx.doi.org/10.1016/j.desal.2011.

01.006.
[104] Ekechukwu O, Norton B. Review of solar-energy drying systems II: an overview of solar drying technology. Energy Convers Manag 1999;40:615–55. http://dx.doi.org/10.1016/S0196-8904(98)00093-4.
[105] Tyagi VV, Panwar NL, Rahim NA, Kothari R. Review on solar air heating system with and without thermal energy storage system. Renew Sustain Energy Rev 2012;16:2289–303. http://dx.doi.org/10.1016/j.rser.2011.12.005.
[106] El Khadraoui A, Bouadila S, Kooli S, Guizani A, Farhat A. Solar air heater with phase change material: an energy analysis and a comparative study. Appl Therm Eng 2016;107:1057–64. http://dx.doi.org/10.1016/j.applthermaleng.2016.07.004.
[107] Lv P, Liu C, Rao Z. Experiment study on the thermal properties of paraffin/kaolin thermal energy storage form-stable phase change materials. Appl Energy 2016;182:475–87. http://dx.doi.org/10.1016/j.apenergy.2016.08.147.
[108] Kapsalis V, Karamanis D. Solar thermal energy storage and heat pumps with phase change materials. Appl Therm Eng 2016;99:1212–24. http://dx.doi.org/10.1016/j.applthermaleng.2016.01.071.
[109] Veerakumar C, Sreekumar A. Phase change material based cold thermal energy storage: materials, techniques and applications - A review. Int J Refrig 2016;67:271–89. http://dx.doi.org/10.1016/j.ijrefrig.2015.12.005.
[110] Zhang N, Yuan Y, Du Y, Cao X, Yuan Y. Preparation and properties of palmitic-stearic acid eutectic mixture/expanded graphite composite as phase change material for energy storage. Energy 2014;78:950–6. http://dx.doi.org/10.1016/j.energy.2014.10.092.
[111] Pielichowska K, Pielichowski K. Phase change materials for thermal energy storage. Prog Mater Sci 2014;65:67–123. http://dx.doi.org/10.1016/j.pmatsci.2014.03.005.
[112] Tyagi VV, Buddhi D. PCM thermal storage in buildings: a state of art. Renew Sustain Energy Rev 2007;11:1146–66. http://dx.doi.org/10.1016/j.rser.2005.10.002.
[113] Enibe SO. Thermal analysis of a natural circulation solar air heater with phase change material energy storage. vol. 28. 2003. 〈http://dx.doi.org/10.1016/S0960-1481(03)00071-5〉.
[114] Rabin Y, Bar-Niv I, Korin E, Mikic B. Integrated solar collector storage system based on a salt-hydrate phase-change material. Sol Energy 1995;55:435–44. http://dx.doi.org/10.1016/0038-092X(95)00074-2.
[115] Morrison DJ, Abdel-Khalil SI. Effects of phase-change energy storage on the performance of air-based and liquid-based solar heating systems. Sol Energy 1978;20:57–67.
[116] Jurinak JJ, Abdel-Khalik SI. Properties optimization for phase-change energy storage in air-based solar heating systems. Sol Energy 1978;21:377–83. http://dx.doi.org/10.1016/0038-092X(78)90169-X.
[117] Hammou ZA, Lacroix M. A new PCM storage system for managing simultaneously solar and electric energy. Energy Build 2006;38:258–65. http://dx.doi.org/10.1016/j.enbuild.2005.06.008.
[118] Hammou ZA, Lacroix M. A hybrid thermal energy storage system for managing simultaneously solar and electric energy. Energy Convers Manag 2006;47:273–88. http://dx.doi.org/10.1016/j.enconman.2005.01.003.
[119] Al-Alili A, Hwang Y, Radermacher R. Review of solar thermal air conditioning technologies. Int J Refrig 2014;39:4–22. http://dx.doi.org/10.1016/j.ijrefrig.2013.11.028.
[120] Al-Alili A, Hwang Y, Radermacher R. A hybrid solar air conditioner: experimental investigation. Int J Refrig 2014;39:117–24. http://dx.doi.org/10.1016/j.ijrefrig.2013.10.006.
[121] Al-Alili A, Hwang Y, Radermacher R, Kubo I. A high efficiency solar air conditioner using concentrating photovoltaic/thermal collectors. Appl Energy 2012;93:138–47. http://dx.doi.org/10.1016/j.apenergy.2011.05.010.
[122] El Fadar A, Mimet A, Azzabakh A, Pérez-García M, Castaing J. Study of a new solar adsorption refrigerator powered by a parabolic trough collector. Appl Therm Eng 2009;29:1267–70. http://dx.doi.org/10.1016/j.applthermaleng.2008.06.012.
[123] Sharaf OZ, Orhann MF. Concentrated photovoltaic thermal (CPVT) solar collector systems: part II - Implemented systems, performance assessment, and future directions. Renew Sustain Energy Rev 2015;50:1566–633. http://dx.doi.org/10.1016/j.rser.2014.07.215.
[124] Sandnes B, Rekstad J. A photovoltaic/thermal (PV/T) collector with a polymer absorber plate. Exp Study Anal Model Sol Energy 2002;72:63–73. http://dx.doi.org/10.1016/S0038-092X(01)00091-3.
[125] Fujisawa T, Tani T. Optimum design for residential photovoltaic-thermal binary utilization system by minimizing auxiliary energy. Electr Eng Jpn 2001;137:28–35. http://dx.doi.org/10.1002/eej.1077.
[126] Kalogirou SA, Tripanagnostopoulos Y. Industrial application of PV/T solar energy systems. Appl Therm Eng 2007;27:1259–70. http://dx.doi.org/10.1016/j.applthermaleng.2006.11.003.
[127] Wang X, El-Farra NH, Palazoglu A. Optimal scheduling of demand responsive industrial production with hybrid renewable energy systems. Renew Energy 2016;100:53–64. http://dx.doi.org/10.1016/j.renene.2016.05.051.
[128] Douani M, Labbaci A, Hadj Benaichouche H. Analysis of the energetic feasibility of parabolic trough collectors integrated in solar towers in Adrar area. Energy Proc 2013;36:1085–100. http://dx.doi.org/10.1016/j.egypro.2013.07.124.
[129] Hachicha AA, Rodriguez I, Capdevila R, Oliva A. Heat transfer analysis and numerical simulation of a parabolic trough solar collector. Appl Energy 2013;111:581–92. http://dx.doi.org/10.1016/j.apenergy.2013.04.067.
[130] Larraín T, Escobar R, Vergara J. Performance model to assist solar thermal power plant siting in northern Chile based on backup fuel consumption. Renew Energy 2010;35:1632–43. http://dx.doi.org/10.1016/j.renene.2010.01.008.
[131] Bishoyi D, Sudhakar K. Modeling and performance simulation of 100 MW PTC based solar thermal power plant in Udaipur India. Case Stud Therm Eng 2017;10:216–26. http://dx.doi.org/10.1016/j.csite.2017.05.005.
[132] Nation DD, Heggs PJ, Dixon-Hardy DW. Modelling and simulation of a novel Electrical Energy Storage (EES) Receiver for Solar Parabolic Trough Collector (PTC) power plants. Appl Energy 2017;195:950–73. http://dx.doi.org/10.1016/j.apenergy.2017.03.084.
[133] Qiu Y, Li M-J, He Y-L, Tao W-Q. Thermal performance analysis of a parabolic trough solar collector using supercritical $CO_2$ as heat transfer fluid under non-uniform solar flux. Appl Therm Eng 2016. http://dx.doi.org/10.1016/j.applthermaleng.2016.09.044.
[134] Price H. A Parabolic Trough Solar Power Plant Simulation Model. ASME 2003 Int Sol Energy Conf 2003:665–73. 〈http://dx.doi.org/10.1115/ISEC2003-44241〉.
[135] Bradshaw RW, Siegel NP. Molten Nitrate Salt Development For Thermal Energy Storage In Parabolic Trough Solar Power Systems. Proc 2nd Int Conf Energy Sustain:631–637. 〈http://dx.doi.org/10.1115/ES2008-54174〉; 2008.
[136] Eck M, Zarza E, Eickhoff M, Rheinländer J, Valenzuela L. Applied research concerning the direct steam generation in parabolic troughs. Sol Energy 2003;74:341–51. http://dx.doi.org/10.1016/S0038-092X(03)00111-7.
[137] Pacheco JE, Showalter SK, Kolb WJ. Development of a molten-salt thermocline thermal storage system for parabolic trough plants. J Sol Energy Eng 2002;124:153–9. http://dx.doi.org/10.1115/1.1464123.
[138] Odeh SD, Morrison GL, Behnia M. Modelling of parabolic trough direct steam generation solar collectors. Sol Energy 1998;62:395–406. http://dx.doi.org/10.1016/S0038-092X(98)00031-0.
[139] Muñoz J, Abánades A. Analysis of internal helically finned tubes for parabolic trough design by CFD tools. Appl Energy 2011;88:4139–49. http://dx.doi.org/10.1016/j.apenergy.2011.04.026.
[140] Farooq M, Raja IA. Optimisation of metal sputtered and electroplated substrates for solar selective coatings. Renew Energy 2008;33:1275–85. http://dx.doi.org/10.1016/j.renene.2007.06.025.
[141] De Jong P, Sánchez AS, Esquerre K, Kalid RA, Torres EA. Solar and wind energy production in relation to the electricity load curve and hydroelectricity in the northeast region of Brazil. Renew Sustain Energy Rev 2013;23:526–35. http://dx.doi.org/10.1016/j.rser.2013.01.050.
[142] Lauterbach C, Schmitt B, Jordan U, Vajen K. The potential of solar heat for industrial processes in Germany. Renew Sustain Energy Rev 2012;16:5121–30. http://dx.doi.org/10.1016/j.rser.2012.04.032.
[143] Fernndez-Garc A, Zarza E, Valenzuela L, Prez M. Parabolic-trough solar collectors and their applications. Renew Sustain Energy Rev 2010;14:1695–721.
[144] Lüpfert E, Riffelmann K-J, Price H, Burkholder F, Moss T. Experimental Analysis of Overall Thermal Properties of Parabolic Trough Receivers. J Sol Energy Eng 2008;130:021007. http://dx.doi.org/10.1115/1.2888756.