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

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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.

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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].

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

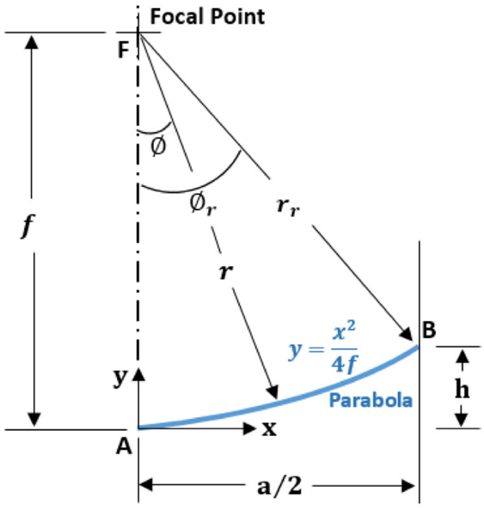

Fig. 1. Section of a linear parabolic concentrator showing major dimensions and the x, y coordinates [21].

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