Renewable and Sustainable Energy Reviews 91 (2018) 193–204

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

A review on parabolic trough/Fresnel based photovoltaic thermal systems

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ARTICLE INFO

Keywords:
Photovoltaic thermal
Fresnel
Trough
Solar collectors

ABSTRACT

The concentrating photovoltaic thermal systems are of much interest among all photovoltaic thermal units which have recently been developed. The trough collectors and Fresnel lenses are more significant in case of concentrating devices, and both are the linear parabolic collectors which have been commercialized well. The numerous publications about these collectors show their importance in the efficient cogeneration of heat and power. Therefore, it is interesting to gather and discuss all the related research papers in an article to show the history as well as the latest developments in this field. This study provides a critical review on the trough/Fresnel based photovoltaic thermal systems. The chapters, containing trough and Fresnel lens, are categorized into three parts as experimental, hybrid studies, and analytical-simulation works. With this regard, the experimental works are summarized in individual tables for each mentioned category. To conclude the survey, some gaps are identified, and suggestions are recommended for future works.

1. Introduction

Solar energy is one of the most common sources which is known as a sustainable and available resource [1,2]. Solar technologies have been progressed in both active (PV modules and solar thermal technologies) and passive solar techniques. Among those, the solar thermal technologies, including flat or parabolic collectors, have become more prominent in the case of producing process heat. The linear collectors are comprised of trough, Fresnel, and compound concentrating systems which focus the sun radiation on a special focal point to raise the process fluid temperature. Specifically, the trough and Fresnel technologies have been commercialized in a broad range. Therefore, we provide an in-depth analysis of the literature around the mentioned fields. The parabolic trough collectors are characterized as the long reflectors, equipped with a receiver pipe located in the central part, above the mirrors, in which the fluid flows. Likewise, Fresnel lenses are linear concentrators with a short focal length or large aperture.

However, to the best of our knowledge, some studies have been conducted regarding these specified fields, which demonstrate the specific development of solar thermal technology [3–6]. Regarding the parabolic trough technology, the pioneer designs were constructed in 1866 by Mouchout [7]. Then, Shuman [8] and Ericson [9] worked on several examinations to attain a better construction. In 1975, the diverse types of trough collectors were built by Shaner and Duff [10]. Regarding the linear Fresnel lenses, the first prototype was built by a French physicist, Augustin-Jean Fresnel, in 1822. The invention was on the basis of glass ring prisms for bending the incoming radiation to a narrow beam [11]. In 1990, the first commercialized concentrating solar plant, which was equipped with parabolic trough collectors, was used in California for the purpose of generating electricity [12]. Although no solar thermal power plant was constructed during 1991–2005, a number of developed technologies and plants were proposed gradually [3]. Hence, some experimental designs were carried out by researchers for improving the solar cells array and the efficiency in trough concentrators [13,14]. For the Fresnel lenses, many documents are observed in case of rising the performance; most importantly, by using two-stage devices known as the primary optical element (POE) and the secondary optical element (SOE) [15,16]. Besides, analytical and simulation studies were introduced using some new methodologies, which mostly focused on the ray tracing methods [17–19]. The hybrid cases were also proposed as a novel technology to develop a better combination and increase the efficiency. Among those, the splitting technique was one of the most popular designs in both trough and Fresnel lens cases [20–23].

The study by Tyagi et al. [24], in 2012, showed an overview of hybrid PV/T collectors during 30 years. The major part of their study was allocated to a wide range of solar energy conversion into heat and electricity. Likewise, Zhang et al. [25] presented a review on the hybrid concentrating PV/T technologies, the splitting and cooling devices in particular. Since the thermal efficiency has become popular in the CPV devices, Kumar et al. [26] conducted a study on the recent developments of photovoltaic thermal technologies. Sharaf and Orhann [27,28] prepared a comprehensive review, which was related to the CPV/T advances in two parts. In the first part, they assessed the fundamental,

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https://doi.org/10.1016/j.rser.2018.03.114
Received 1 March 2017; Received in revised form 31 March 2018; Accepted 31 March 2018
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Nomenclature

PV	Photovoltaic
POE	Primary Optical Element
SOE	Secondary Optical Element
PV/T	Photovoltaic / Thermal
CPV	Concentrating Photovoltaic
CPV/T	Concentrating Photovoltaic / Thermal
GaAs	Gallium Arsenide
CFD	Computational Fluid Dynamics
FVM	Finite Volume Method
MCRT	Monte Carlo Ray-Trace
k	Thermal conductivity (W/m K)
LCOE	Levelised cost of energy
Si	Silicon
2D	Two Dimension
EES	Engineering Equation Solver
CAP	Concentration-Acceptance Angle Product
FK	Fresnel Kohler
F-RXI	Fresnel uses RXI as SOE
RXI	Rays of refraction (R), reflection (X) and total internal reflection (I)
DFK	Dome-Shaped FK
RTP	SOEs like Inverted Truncated Pyramid
SILO	Single Optical Surface
XTP	Hallow Refractive Truncated Pyramid
FK_9	9-fold FK
FK_4	4-fold FK
PMMA	Poly Methyl Methacrylate
DCCPC	Dielectric-Cross Compound-Parabolic-Concentrator
RTP	Refractive Truncated Pyramid
TP	Truncated Pyramid
LED	Light-Emitting Diode
BK_7	A high quality glass
UV	Ultraviolet

design, and technologies. Then, the performance studies and the future directions were discussed in the second part. In terms of special concentrators, Fernández-García et al. [29] presented a broad-gauged survey regarding the constructed and under-construction trough collectors. In another study, the detailed examination of the durability of Fresnel lenses was well investigated by Miller and Kurtz [30]. They also investigated the utilized materials, thermal decomposition, soil, and some characterizations of Fresnel lenses. In a comprehensive review, which has been recently published, the designs, development, and comparisons of the compound parabolic concentrators have been analyzed for achieving the breakthrough technologies of solar energy. This paper reviews the literature concerning the usefulness of the application in this field, but the Fresnel and trough subjects were not the concern of the work [31].

As it is obvious, there are two reviews related to the hybrid CPV/Ts. Also, three reviews were accounted for a significant proportion of CPV/T devices, of which one was allocated to a special case study. However, the literature reviews show some topics as general fields of PVTs, trough collectors, and failure modes and durability for Fresnel collectors. With the progressing trend in terms of solar collectors, studying the distinctive categories will lead to an optimized solution for extracting the brainstorm technologies and accessing to the efficient results. In addition, no literature survey was found in the field of gathering and analyzing the studies about photovoltaics, coupled with linear parabolic collectors. As it was abo mentioned above, the two main types of the linear parabolic collectors are trough and Fresnel, which are focused in this survey. To catch the aim with this respect, the recent works including either general or detailed technical subjects were taken into account. The aim of this review would be gathering a database for all the literature about trough PVTs and Fresnel-based PVTs, which could help the researchers to know about what have been done and what areas are capable for more development. The experimental and analytical together with the hybrid studies are described for the mentioned concentrators, thoroughly.

2. Experimental studies

2.1. Trough collectors

There is a consensus among the scientists on the importance of experimental works in order to introduce new devices for collecting the sun's radiant heat. In 1866, Augustin Mouchout constructed the first concentrating trough collector [7]. After that, many designs and experiments were conducted by Shuman and Ericson [8,9]. In 1913, Shuman built an irrigation pump, for utilizing the energy collected by a trough collector. Then, the construction process was improved by using different technologies. For instance, the focal axis of the photovoltaic trough collector was covered by glass tubes. In 1975, Shaner and Duff [10] built and tested different trough collectors, which varied by the performance parameters. According to their experimental section, one collector was employed with a plywood shell, while another one was constructed using fiberglass materials. Furthermore, trough collectors have been commercialized by the US agreement with the Luz International Limited for electricity generation in nine plants. The total installed capacity of these nine solar power plants was 354 MW, which ranged in 14–80 MW per each plant. After that, some power plants were built with the aim of improving the efficiency and reducing the costs [32].

In 2008, Xu et al. [13] conducted some experimental works on solar cell arrays for a trough concentrator. They compared different solar cell array materials like crystalline silicon cell, polysilicon cell, poly cell, super cell, and GaAs cell, of which the GaAs led to the best efficiency. Then, a study was performed by Yongfeng et al. [33], using a 2 m^2 trough CPV with an optical efficiency of 0.69 for the reflective mirror. Different types of solar cells (single crystal, polycrystalline, supper cell, and GaAs) were tested, among which, the GaAs resulted in the highest electrical efficiency. In 2011, the impact of the applied materials for constructing concentrating PV/T trough devices was investigated by Li et al. [34]. Both electrical and thermal efficiencies of a super cell array, a GaAs, and a concentrating silicon cell array were examined with a 10 m^2 concentrating trough collector. With respect to the thermal efficiency, the super cell achieved the best results. Li et al. [35], in 2011, performed another experimental study on the performance of a CPV/T trough collector, using different solar cell materials. They tested a single crystalline, a polycrystalline super cell, and a GaAs cell in their research. The mentioned CPV/T trough with a geometric concentration ratio of 16.29 resulted in the best results for the GaAs array. In another study, both theoretical calculations and experimental investigations on the performance of a CPV/T trough were carried out for four types of solar cells by Li et al. [36]. In their study, different cell materials including single crystalline, super crystalline, and GaAs were examined. The results showed that the GaAs cells had the best performance at the higher concentration ratio. In 2012, the performance analysis of a one-dimensional concentrating photovoltaic trough was performed by Ji et al. [14]. In this paper, supper cell array and GaAs cells were proposed to formulate the model. While, the model was validated by an experimental setup using a 2 m^2 CPV/T trough collector.

Change et al. [37], in 2012, constructed a multiple chamber trough concentrator device and compared the efficiency with the flat-plate and simple trough CPV/Ts. The proposed case could increase the output

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