Renewable and Sustainable Energy Reviews 81 (2018) 473–492

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Concentrating photovoltaic thermal (CPVT) collectors and systems: Theory, performance assessment and applications

Reza Daneshazarian[a], Erdem Cuce[b,*], Pinar Mert Cuce[b], Farooq Sher[c]

[a] Department of Renewable Energies Engineering, Faculty of New Sciences & Technologies, University of Tehran, Tehran, Iran
[b] Department of Mechanical Engineering, Faculty of Engineering, University of Bayburt, Dede Korkut Campus, 69000 Bayburt, Turkey
[c] Department of Chemical Engineering, Faculty of Engineering, University Park Campus, University of Nottingham, Nottingham NG7 2RD, United Kingdom

ARTICLE INFO

Keywords:
CPVT collectors
Concentration ratio
Operating temperature
Thermal and electrical efficiency
COP
Thermodynamic model
Payback period

ABSTRACT

Concentrating photovoltaic thermal (CPVT) collectors and systems are very popular in both domestic and industrial solar energy applications. CPVT collectors provides incomparably greater thermal and electrical outputs compared to stand alone PV or hybrid PVT systems as incoming solar energy is maximised inside the unit via energy-efficient concentrators. Within the scope of this paper, a comprehensive review on CPVT collectors and systems is proposed. For an easier assessment of the findings through state-of-the-art analyses on CPVT collectors, the review is presented in a thematic way. Historical overview of the technology is followed by the detailed description of a CPVT collector with main system elements and thermodynamic performance definitions. The review also covers thermal and electrical performance analysis of CPVT collectors using water or air as working fluid, analytical, numerical, simulation and experimental works for performance evaluation of different design configurations of CPVT systems and qualitative analysis of electrical and thermal energy generation. The impacts of concentrator type and concentration ratio on system efficiency, operating temperature and coefficient of performance (COP) are analysed in detail. It is observed from the findings that CPVT collectors are promising devices in market, and they have a good potential to be competitive with conventional power generation systems in the near future.

1. Introduction

Solar energy is one of the most promising sources of energy as it supplies clean, limitless, environmentally-friendly energy and power [1–3]. The annual absorbed energy by the Earth from the Sun is about 3.85 million EJ [4]. Suitable collectors such as parabolic trough collectors (PTC), linear Fresnel reflectors (LFR), and concentrating photovoltaic thermal (CPVT) collectors have a great potential to enhance the solar radiation gathering process [5]. Coupling of photovoltaic (PV) systems with concentrator units such as parabolic trough and dish collectors has been an attractive field for solar researches from early 1980s [6]. The CPVT collector is one of the last improved and efficient hybrid collectors. The first CPVT collector was made in Sandia National Laboratories [7]. The concentrated photovoltaic (CPV) and photovoltaic thermal (PVT) systems are the results of this interest. Several CPVT systems have been designed and manufactured for numerical and experimental investigations. CPVT collectors have high optical and thermal efficiencies. For example, global efficiency of these systems is more than 65.1% [8] and the outlet temperature of working fluid is approximately 200 °C [9]. The costs and payback period of said systems are very low according to their performance. For instance, cost of electricity in a CPVT collector is 2.37 $/W [10] and total electrical and thermal costs are 8.7 $/W [11].

There are several works in literature on the field of PVT [12–14] and CPV systems [15–19]. Also, there is a review on CPVT systems conducted by Sharaf and Orhan [18]. However, there is not a review on the fundamentals and state-of-the-art of CPVT systems with domestic and industrial applications. In this research, a brief and complete review on the CPVT technology focusing on the fundamentals, concept, design, and test of CPVT solar collectors is presented. In the review, CPVT collectors are split into system elements to clarify the subsystems with their functionality and role in overall system performance. It is well-documented in literature that both CPV and concentrated solar thermal systems are the basic parts of a CPVT collector, so studying these elements would help understanding the complete CPVT system.

The most important factor in the CPVT collectors is their concentration ratio. CPVT systems with high concentration ratio could lead to a small cell surface, so this cost saving issue could be used for the efficient multi-junction solar cells. The multi-junction solar cells have

* Corresponding author.
E-mail address: erdemcuce@gmail.com (E. Cuce).

http://dx.doi.org/10.1016/j.rser.2017.08.013
Received 9 May 2017; Received in revised form 4 July 2017; Accepted 7 August 2017

Nomenclature

A	aperture area (m^2)
E	energy (J)
FF	fill factor
G	solar intensity (W/m^2)
h	Planck's constant
I	current (A)
q	electronic charge
T	temperature (K)
V	voltage (V)
V_g	band gap voltage (V)

Subscripts

amb	ambient
c	collector
c.ideal	ideal conversion
ele	electrical
ex	exergy
ex,in	input exergy
max	maximum
oc	open circuit
pc	power conversion efficiency
PES	primary energy saving
PES-ele	primary energy saving to electrical energy
PES-th	primary energy saving to thermal energy
sc	short circuit
sun	sun
th	thermal

Greek symbols

δ	electrical to thermal ratio
η	efficiency
k	Boltzmann's constant
λ	wavelength (nm)

high performance and efficiency range that could reach more than 40% [20–22]. For an efficient CPVT system, the PV modules are expected to have an efficiency above 30% [23–25].

In the design of the concentrating units in a CPVT system, it can be asserted that dish parabolic, parabolic trough, and linear Fresnel reflectors are the most common types. It needs to be mentioned that linear and point concentration is the main difference in the concentration process of the CPVT collectors. There are great interests and advances in CPVT technologies within the last decade. Among the alternative concentrating units, Fresnel lens reflectors are considered as the most suitable collector type to be utilised in CPVT systems. These collectors have several advantages such as small size, being lightweight and notably low production costs. To confirm the said benefits, Araki et al. [26] investigate a CPVT system using Fresnel lenses. Their collector efficiency is found to be 25.8% and the nominal power generation 30 kW. The review study done by Xie et al. [15] on the concentrated solar application using LFR also report such benefits.

CPV systems concentrate the incoming solar energy on the PV cells. As it is well-known in energy market that high performance PV cells are expensive and CPV collectors overcome this challenge. In CPV collectors, concentrated solar beam is reflected on the PV cells which provides a cheaper process than standalone PV systems. Therefore, the efficiency of such systems would be higher than that of a conventional PV cell and this enhancement is achieved with lower costs. On the other hand, the number of PV cells is remarkably reduced by using of CPV collectors. Also, PVT collectors are in the centre of interest to generate both thermal and electrical energy simultaneously. The back surface temperature of PV cells would be a waste heat recovery source. In order to maximise the performance of PV cells, the waste heat at the back of PV cells can be recovered, and this thermal energy content can be utilised for other applications such as space heating or water heating. CPVT systems are basically a hybrid application of PVT and CPV collectors for having better electrical and thermal performance. There are two disadvantages of PVT systems; First, generating desired amount of electrical energy from PV cells needs high investment costs. Second, the thermal energy of these systems are used just for low-temperature applications. In a CPVT system both of these demerits are overcome by maintaining the PV cells in a moderated temperature and utilizing the spectrum concentration.

Design and manufacturing of CPVT systems is the most important and sensitive part of these collectors. At first step, the use of this collector needs to be clarified, either it would be used for domestic applications or industrial processes. Key factors need to be discussed in this respect. Vital merits of CPVT systems are the same as PVT and CPV collectors such as CO_2 free system, minimising fossil fuel consumption and waving water resources. Key factors in the design of CPVT systems are similar to CPV and PVT systems in most cases. CPVT systems have multi-output generation, high-value thermal energy, high total efficiency, less number of PV cells, and low cell temperatures. On the other hand, they have also some drawbacks such as their complexity, PV overheating, and high PV series resistance.

2. Thermodynamic overview

In a common CPV system more than the half of the radiation energy is transformed to waste heat [27]. But in a CPVT system, most of the waste heat enters to the heat extraction section. CPVT collector has higher useful energy in comparison with other solar collectors. According to second law of thermodynamics, it is understood that the electrical and thermal useful outputs of CPVT collectors are not equal, even if they could be equal according the first law. Coventry and Lovegrove [28] study different methods for finding an electrical to thermal ratio for the useful energy conversion in a PVT system. The ratio definition is given as follows [29]:

$$E_{ele.eq} = \frac{E_{th}}{\delta} + E_{ele} \tag{1}$$

Studying the exergy analysis of a CPVT collector which is in relation with second law of thermodynamics, is more important than the energy analysis based on first law of thermodynamics. Exergy analysis is basic and considered as the best optimization method for CPVT collectors [28]. Huang et al. [29] represent the primary energy saving (PES) efficiency for a CPVT systems as follows:

$$\eta_{PES} = \frac{E_{ele}}{\eta_{PES-ele}} + \frac{E_{th}}{\eta_{PES-th}} \tag{2}$$

The thermal efficiency is multiplied by a Carnot factor by Otanicar et al. [30] in their CPVT model. The fraction of the thermal energy that is converted into electrical output is considered to be 0.5, which is the ideal Carnot efficiency. Xu et al. [31] perform an experimental research on the low concentrating PVT system. Their CPVT system is proposed to be used for water heating and their schematic diagram is shown in Fig. 1. Their results reveal that the temperature of 80 L water rises from 30.9 to 70 °C and the flow rate for the circulating water is 0.45 m^3/h for the solar radiation and the ambient temperature variations illustrated in Fig. 2.

The PV section has an important impact on the electrical and thermal performance of CPVT collectors. Therefore, the thermody-