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Numerical simulation of a concentrating photovoltaic-thermal solar system combined with thermoelectric modules by coupling Finite Volume and Monte Carlo Ray-Tracing methods

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ABSTRACT

During the last decades, the adoption of more strict safety and environmental regulations, as well as a rise in energy costs, sparked an increasing interest in the design of renewable energies systems, particularly solar systems, to supply both electrical power and heat. Because of their capability to simultaneously supply both electricity and heat, concentrating photovoltaic-thermal and thermoelectric hybrid systems have recently attracted scholarly attention. In this study, a detailed three-dimensional computational model of a novel concentrating photovoltaic-thermal solar system combined with thermoelectric modules in an integrated design with a triangular absorber and corresponding numerical simulations are presented. For this purpose, a three-dimensional integrated model combined the Finite Volume method with the Monte Carlo Ray-Tracing method is employed. After validating simulation results and providing some discussions on the effects of temperature and cooling on the photovoltaic modules performance, the impacts of varying two design parameters of the system, the aperture width of the reflector and the apex angle of the absorber, on the solar energy flux distribution and output power of photovoltaic modules are discussed. Finally, considering the conditions of the case study, a range of aperture widths for the reflector and apex angles for the triangular absorber are proposed.

1. Introduction

The cardinal importance of energy in the economic development of any country is well recognized universally. Given that vast amounts of present energy demand are supplied by consumption of non-renewable fossil fuels [1], challenges of fossil fuel depletion and greenhouse gases emission have arisen [2]. To address these unprecedented challenges, renewable energy sources, separately or in tandem, have recently gained considerable attention worldwide in order to move towards environmental sustainability by taking the place of diminishing and environmentally harmful fossil fuels [3]. The abundance of solar energy, considered as the cleanest and most widely distributed source of renewable energy, promises efficient and reliable methods to meet currently increasing energy needs, both electricity and heating [4]. Photovoltaic (PV) modules and thermal collectors have been widely used to convert solar energy to electricity and heat, respectively, in recent decades. These systems, nonetheless, are restricted to supplying either electrical power or heat in most cases [5].

Since PV cells use a mere fraction of the incident solar radiation to generate electrical power and the remaining portion is mainly turned into waste heat resulting in the rise of PV cell temperature and consequent drop of module efficiency, more recently, hybrid photovoltaic-thermal (PVT) systems to generate both electricity and heat have been examined [6]. In the PVT system, the simultaneous cooling of the PV module enhances the electrical conversion efficiency of the system and, thereby, leads to a more cost-effective system. Owing to these technical and economic merits, numerous applications of PVT systems have been reported from all over the world. Kasaeian et al. [7] examined the potential of solar combined heat and Power (CHP) systems, such as PVT and CPVT systems, in a review article. In another recent study, Al-Waeli et al. [8] also summarized different aspects of PVT systems existing in the literature in order to underline their key points which may be found useful in future works. However, PVT systems are limited to low-temperature waste heat production (30–80 °C) [5] and also suffer high investment costs due to the need for employing a myriad of PV cells and, consequently, thermal counterparts to supply a practical flow of electricity [9].

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Nomenclature

A_a	aperture area of concentrator (m^2)
A_{PVT}	area of PV modules (m^2)
$\dot{m}$	mass flow rate of working fluid (kg/s)
T	temperature (K)
T_o	outlet temperature of working fluid (K)
T_i	inlet temperature of working fluid (K)
T_{PV}	temperature of the PV cells (K)
T_{ref}	temperature of the PV cells at reference condition (K)
T_{amb}	ambient air temperature (K)
T_{cold}	temperature of cold side of the TE module (K)
T_{hot}	temperature of hot side of the TE module (K)
I	electrical current (A)
I_{mpp}	maximum power point current (A)
I_{sc}	short circuit current (A)
I_{SCR}	PV cell electrical short-circuit current at reference condition (A)
V	electrical voltage (V)
V_{oc}	open circuit voltage (V)
V_{mpp}	maximum power point voltage (V)
P_m	maximum electrical power (W)
P_{el}	total electrical power (W)
P_{th}	output thermal power (W)
P_{PV}	output power of PV modules (W)
P_{TE}	output power of TE modules (W)
p	pressure (Pa)
C_p	specific heat (J/kg K)
Re	Reynolds number
Pr	Prandtl number
x, y, z	Cartesian coordinates (m)
u, v, w	x, y, z velocity components (m/s)
g	gravity (m/s^2)
h	heat transfer coefficient (W/m^2K)
R	resistance (Ω)
W	aperture width (m)
L	length (m)
a	length of side of triangular absorber (m)
Ib	incident solar radiation (W/m^2)
Q''_{in}	heat flux (W/m^2)
Z	figure of merit
η_{el-TE}	electrical conversion efficiency of TE module (%)
η_{el-PV}	electrical conversion efficiency of PV array (%)
η_{th}	thermal efficiency (%)
$\eta_{DC/AC}$	efficiency of converting DC current to AC current (%)
η_{pv-teg}	overall efficiency of the PV and TE modules (%)
ρ	density ($kg/\ m^3$)
μ	dynamic viscosity (Pa s)
β	temperature coefficient (1/K)
α	apex angle of triangular absorber (°)
ρ_r	reflectance of reflector
τ_g	transmittance of the glass
α_a	absorptance of the receiver

Abbreviations and acronyms

MCRT	Monte Carlo Ray-Tracing
FVM	Finite Volume Method
PV	photovoltaic
TE	thermoelectric
CPTV	concentrating photovoltaic-thermal
PTC	parabolic trough collector
PVT	photovoltaic-thermal
CHP	combined heat and power
CSP	concentrated solar power
PSC	parabolic solar concentrator
LCF	Local Concentration Factor

small area is a practical approach to generate high-temperature thermal energy. New innovations in concentrated solar power (CSP) technology have led to more cost-effective solar systems [10]. For instance, concentrating photovoltaic-thermal (CPVT) systems, the combination of PV technology, solar thermal technology, and reflective or refractive solar concentrators, have come to the focus of attention since they offer higher electrical conversion efficiencies than PVT systems and supply medium- and high-temperature thermal energy with a wide range of applications in residential buildings, industrial process heat (IPH) applications, and power plants [5]. Parabolic trough CPVT systems, one of the main types of high-concentration CPVT systems with a linear focus, have recently been investigated in few researches. Their heat transfer and excess heat have been examined using different methods. Redpath et al. [11] experimentally compared a flat plate PVT (FP-PVT) system with headers and risers for heat removal with a fixed linear axis Compound Parabolic Concentrating solar PVT (CPC-PVT) system with a heat-pipe for removal of solar gain. Both systems benefitted from polycrystalline silicon solar photovoltaic cells adhered to the absorber. Heat loss coefficient was measured 4.1 W/(m^2 K) for the FP-PVT collector and 3.5 W/(m^2 K) for the CPC-PVT solar collector respectively. Moreover, the combined efficiency of the FP-PVT was 66.8%, while it was 53.4% for CPC-PVT. In another recent experimental study, Karathanassis et al. [12] designed and evaluated a novel parabolic-trough CPVT system. They utilized and compared three variations of the system receiver incorporating different PV-module and heat-sink designs in order to attain maximum cooling and heat recovery, and reported that the prototype CPVT system had an overall efficiency of approximately 50% (44% thermal and 6% electrical efficiencies, respectively). CPTV systems, nonetheless, have a long way to go before becoming mature enough to be commercialized. In this way, theoretical and simulation studies can play a major part since experimental ones are usually costly and time-consuming.

One of the initial steps in the simulation of a parabolic trough CPVT system is to determine the concentrated solar flux distributions. Since the 1970s, numerous researches have been conducted on the use of numerical methods to investigate the heat flux distributions characteristics of parabolic solar concentrators (PSCs) [13]. Earlier studies, either one-dimensional or two-dimensional, assumed the solar flux and flow were uniform or constant in the parabolic trough collectors; moreover, there were a plethora of correlations in the models based on an assumption of a uniform or constant temperature. In reality, concentrated solar flux on the outer surface of the absorber is non-uniform, resulting in asymmetric heating of the flow. Hence, in order to carry out more comprehensive studies on detailed characteristics of the photothermal conversion and to accurately predict the convective heat transfer rate for this type of flow, in recent years, a number of three-dimensional numerical models have been developed to consider the nature of the non-uniform concentrated solar flux [14]. For instance, Wirz et al. [15] modeled three-dimensional heat transfer in a parabolic trough solar concentrator (PTC) system by considering the non-uniform distribution of the incident solar radiation, the heat gain/loss around the receiver's circumference and along the system's axis, and the spectral radiative exchange between the various receiver surfaces.

The Monte Carlo Ray-Tracing (MCRT) method has been well established as an efficient and flexible numerical method to simulate the concentrating characteristics of concentrating solar collectors (CSCs) [16]. Several numerical models for simulation of parabolic trough collectors based on the MCRT method have been recently developed,