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Experimental and theoretical model of a concentrating photovoltaic and thermal system

C. Renno *, F. Petito

Department of Industrial Engineering, University of Salerno, Via Giovanni Paolo II, 132, 84084 Fisciano (Salerno), Italy

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ABSTRACT

The experimental and theoretical analysis of a concentrating photovoltaic and thermal system (CPV/T) presented in this paper allows to evaluate the electrical parameters of the system, the concentration factor, the cell temperature in different working conditions and the fluid temperature. In particular, the experimental values of the cell temperature represent the input of a model developed in ANSYS-CFX. This model evaluates the theoretical temperature values of the fluid that flows into the cooling circuit of the CPV/T system, designed with the CATIA software. Hence, both electrical and thermal parameters have been analyzed in order to evaluate the potential energy production of a concentrating photovoltaic and thermal system. Different configurations of the CPV/T system have been analyzed and the value of the concentration factor has been determined by means of an experimental procedure. The experimental and theoretical electric powers are compared in different climatic conditions considering a solar radiation included between 500 and 900 W/m^2. The electric efficiency is also evaluated as function of solar irradiance and cloudiness. Moreover, the fluid temperature as function of the experimental cell temperature is determined in different working conditions by means of the ANSYS model. The fluid temperature is also theoretically determined varying the operating conditions along the circuit. Finally, a study of the electrical and thermal performances represents a key-factor to develop a more complex prototype of a CPV/T system.

1. Introduction

In a concentrating photovoltaic system (CPV) the sunlight is concentrated on triple-junction solar cells by means of an optical device and higher temperatures are also obtained [1]. This has an impact on the electric performances and, differently from the traditional photovoltaic systems, on the possible recovery of thermal energy at high temperature. Hence, the concentrating photovoltaic and thermal systems (CPV/T) allow to obtain electric and thermal energy [2]. Therefore, the heat removal becomes a strategic factor that affects the CPV/T system configuration [3]. Many applications are investigated in literature in order to evaluate the potential of the CPV/T systems. In [4] a review of various cooling technologies available for CPV systems is presented. The technology should be reliable and maintain a low and uniform cell temperature. In [5] the fluid which cools the cells is accumulated in a tank. In [6] a concentrating dish is linked to a system of tubes evacuated to have an efficient thermal energy production. In [7] the performances of a CPV/T system with a Fresnel concentrator are studied. In [8] a new multi-layer manifold micro-channel cooling system for concentrating photovoltaic cells is presented. In [9] a CPV/T system is designed in order to recovery thermal energy and to increase the electric production. In [10] a compound parabolic concentrator is modified to evaluate the performances of a new solar concentrator working simultaneously as electricity generator and thermal collector. In [11] related to the electric, heating and cooling loads of a domestic user, the design and model of a CPV/T system are studied. In [12] the optimized value of the concentration factor able to provide a fluid outlet temperature that satisfies the thermal and cooling demands and to decrease the CPV/T system size, is obtained in each working condition. Hence, there are several CPV/T systems that allow a combined energy production, but it is not possible to obtain a standard configuration [13]. Therefore, it is important to evaluate accurately for each operating condition both the electrical and thermal performances of a CPV/T system. In particular, it is necessary to evaluate the cell temperature that depends on the concentration of the solar radiation, and influences the electrical performances of the same cell. This is basic to evaluate the temperatures reached by the working fluid in a CPV/T system. These evaluations can be carried out both experimentally and theoretically. In [14] a numerical and experimental study of a

* Corresponding author.
E-mail address: crenno@unisa.it (C. Renno).

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Nomenclature

A	area (m^2)
C	concentration factor
CFD	Computational Fluid Dynamics
CPC	compound parabolic concentrator
CPV	concentrating photovoltaic
CPV/T	concentrating photovoltaic and thermal
c	specific heat (kJ/kg K)
d	diameter (m)
FF	factor
G	irradiance (W/m^2)
h	unitary convective conductance (W/m^2 K)
I	current (A)
InGaP/InGaAs/Ge	indium-gallium-phosphide/indium-gallium-arsenide/germanium
K	conductance
m	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
MJ	multi-junction
N	number
P	electric power (W)
T	temperature (°C)
x	space (m)
V	voltage (V)

Greek symbols

α	absorptivity coefficient
η	efficiency
θ	time (s)
σ_t	temperature coefficient (%/°C)

Subscripts

a	air
c	cell
dir	direct
f	fluid
i	indoor
inc	incident
int	intermediate
Kal	Kaleidoscope
mod	module
MPP	maximum power point
o	outdoor
oc	open circuit
opt	optic
ref	reference
SC	short-circuit
t	tube
tot	total
th	theoretical

U-shaped solar energy collector model of a CPV/T system is presented in order to evaluate the maximal thermal and electrical power related to an optimum volumetric flow rate. The simulation of a high concentrating photovoltaic module by means of neuronal networks, adopting the direct normal irradiance spectrally corrected and the cell temperature, is presented in [15]. The model of a linear concentrating photovoltaic system with an active cooling system, is reported in [16]. In [17] the dynamic model of a CPV/T system is theoretically determined by means of the finite element method. In [18] a three dimensional heat transfer model is presented for a design of new concentrating photovoltaic system. So, it can be noted that the thermal recovery depends on the evaluation of the cell temperature whose value cannot easily determined theoretically in each operating condition [19]. The cell temperature, which affects the heat recovery, is strongly linked to the concentration factor [20]; these factors influence several cell parameters such as the photo-generated current [21]. Hence, in this paper a specific configuration of a CPV system is presented and studied. The configuration adopted considers the coupling of a Fresnel lens with a triple-junction solar cell and a kaleidoscope as secondary optics. This kind of system has been only partially treated in literature. In particular, the innovative aspect of the analysis reported in this paper is related to the secondary optics use in order to achieve a high concentration factor. Moreover, the system designed is experimentally analyzed from an electrical and thermal point of view, and the cell electrical performances and its temperature are experimentally determined. Different tests are conducted in order to define the concentration factor reached by the designed CPV scheme in standard conditions. Subsequently, by means of a finite element model built in ANSYS [22] which has as input the experimental cell temperature, the refrigerant fluid temperature is theoretically determined corresponding to different solar radiation and outdoor temperature values. This study analyses the possibility to use a refrigerant fluid, such as a glycol-water solution, for an active cooling of the solar cell in order to obtain also thermal energy. Hence, the ANSYS model allows to evaluate the thermal energy production of a CPV/T system, once experimentally evaluated the cell temperature. Finally, the system electrical performances are also experimentally evaluated taking into account different working conditions.

2. Theoretical model

In order to evaluate accurately the electrical and thermal performances of a CPV/T system, in this paper the cell electric power and its temperature are experimentally determined. In particular, by means of a model built in ANSYS [22], which has as input the cell temperature values experimentally obtained, the cooling fluid temperature is determined corresponding to different working conditions. Photo and scheme of the experimental plant are respectively reported in Figs. 1 and 2. In Fig. 3 the flow-chart of the experimental-theoretical analysis is reported. This study of the electrical and thermal performances represents a key-factor in order to develop a more complex prototype of a CPV/T system. The experimental analysis has been realized following three phases. The first step has been the electrical characterization of the system in the standard conditions and the C evaluation. The second phase analyzes the electrical performances of the CPV system in terms of electric power and efficiency in different conditions. The third step matches the experimental tests with the theoretical analysis developed in ANSYS-CFX. In particular, the experimental values of the cell temperature represent the input of the thermal model which evaluates the cooling fluid temperature of the CPV/T system considered in this paper. The cooling circuit for the ANSYS thermal simulations has been designed with the CATIA software. Hence, both electrical and thermal aspects are analyzed in order to evaluate the energy potential of a CPV/T system.