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Electrical and thermal performance evaluation of symmetric truncated C-PVT trough solar collectors with vertical bifacial receivers

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ABSTRACT

One way to reduce solar collectors' production costs is to use concentrators that increase the output per photovoltaic cell. Concentrating collectors re-direct solar radiation that passes through an aperture into an absorber/receiver. Symmetrical truncated non-tracking C-PVT trough collectors based on a parabola and compound parabolic concentrator (CPC) geometries have been developed. The collector type has a central vertical bifacial (fin) receiver and it was optimized for lower latitudes. In this paper, the electrical and thermal performance of symmetric truncated non-tracking low concentrator PVT solar collectors with vertical bifacial receivers is analysed, through a numerical ray-tracing model software and a multi-paradigm numerical computing environment. A thermal (quasi-dynamic testing method for liquid heating collectors described in the international standard for solar thermal collectors ISO 9806:2013) and electrical performance models were implemented to evaluate the design concepts. The evaluation was made for heating Domestic Hot Water for a Single Family House in Fayoum (Egypt), where CPC geometries with a concentration factor of 1.6 achieved 8 to 13$\%_{rel}$ higher energy yields (in kWh/m^2/year) than the Pure Parabola geometries.

1. Introduction

Photovoltaic-Thermal (PVT) collectors are hybrid solar collectors that simultaneously generate electrical (through PV cells) and thermal energy (through the solar radiation absorbed by the PV cells that is not converted into electricity). These systems can be based on Compound Parabolic Collector (CPC) or on flat plate solar thermal (T) collectors (Sharaf and Orhan, 2015). According to Zondag (2008), PVT collectors can be classified according to their PV cell technology, design (unglazed, glazed, and concentrating), and their heat transfer medium (water and air). Concerning concentrating PVT collectors, Stine and Harrigan (1986) classified this technology as low, medium or high concentration (ratio) system, with the possibility of both stationary and tracking operation. These systems are also known by their low heat losses.

Previous studies showed that the efficiency of PV cells is temperature dependent. For every degree increase in temperature, the cell efficiency decreases between around 0.3% and 0.5%, and for that reason, it is necessary to remove and harvest the excess heat. This increased PV cell temperature leads to a significant efficiency drop since the cells can reach very high temperatures.

In order to carry out the excess thermal energy generated by the PV cells, a cooling fluid is used (generally water with a percentage of glycol to prevent the fluid to freeze), which leads to a decrease in temperature on the solar cells and to higher overall efficiencies (Kramer and Helmers, 2013). This way, the waste heat harvested by the cooling fluid can be used as a cogenerated product and for heating applications (Aste et al., 2014).

According to Davidsson et al. (2010), the combination of reflectors with PVTs is cost-effective since they require less reflective material and are less deep than flat one-sided absorber collectors. This technology also takes advantage of the geometry acceptance angle and the efficiency of the PV cells can be increased by actively cooling the laminated PV.

Incorporating both electrical and thermal system into a single unit decreases the total area dedicated to solar energy devices, by optimizing the use of the solar resource (Lämmle et al., 2016). Nevertheless, this technology faces some challenges, such as partial shadowing. Partial shadowing has been identified by Decker and Jahn (1997), as the main cause for decreasing the energy yield of PV arrays. A Concentrating Photovoltaic-Thermal (C-PVT) non-tracking, to be able to perform at its full electrical potential (no shadowing), needs to ensure that the reflected image of the PV cells in the reflector stays as much as possible in the reflector boundaries. At lower solar altitudes (i.e. morning and afternoon), the reflected image of the PV cells in the reflector is not complete, leading to loss of power, thus lowering the

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Nomenclature

Symbol	Description [Unit]
θ_c	acceptance half-angle [°]
t_a	ambient temperature [°C]
G_b	beam irradiance [W/m^2]
$t_{cell,PVT}$	cell temperature [°C]
C_i	concentration factor [–]
b_0	constant for incident angle modifier
G_d	diffuse irradiance [W/m^2]
c_5	effective thermal capacity [J/m^2.K]
$\eta_{el,STC}$	electrical efficiency at standard testing conditions [–]
f	focal length [mm]
F	focus [–]
x	half aperture [mm]
c_1	heat loss coefficient at $(t_m - t_a) = 0$ [W/m^2.K]
θ	incidence angle [°]
$K_{\theta b}(\theta_L,\theta_T)$	incidence angle modifier for beam radiation [–]
$K_{\theta d}$	incidence angle modifier for diffuse radiation[–]
E_l	long wave irradiance ($\lambda > 3\,\mu$m) [W/m^2]
η_{max}	maximum efficiency [–]
t_m	mean fluid temperature [°C]
$\eta_{0,b}$	peak collector efficiency at $\Delta T = 0$ K [–]
h	receiver height [mm]
ρ	reflectivity [%]
z	reflector height [mm]
c_4	sky temperature dependence of heat loss coefficient [–]
G	solar irradiance [W/m^2]
P_{el}	specific electrical power output [W/m^2]
Q_{th}	specific thermal power output [W/m^2]
u	surrounding air speed [m/s]
β	temperature coefficient of electrical power [%/K]
c_2	temperature dependence of heat loss coefficient [W/m^2.K^2]
c_3	wind speed dependence of heat loss coefficient [J/m^3.K]

Subscripts

CPC	Compound Parabolic Collector
CSP	Concentrating Solar Power
C-PVT	Concentrating Photovoltaic-Thermal
DHW	Domestic Hot Water
IAM	Incidence Angle Modifier
MaReCo	Maximum Reflector Concentration
MCRTM	Monte Carlo Ray-Tracing Method
PP	Pure Parabola
PR	Performance ratio
PTC	Parabolic Trough Collector
PVT	Photovoltaic-Thermal
SFH	Single-Family House
T	Thermal

energy yield. In order to avoid shadowed PV arrays from breaking down, bypass diodes are applied. This allows the current to flow in a different path at the expense of a minor fraction of the total power (Woyte et al., 2003).

At lower latitudes, the solar radiation is characterised by its symmetry over the year. This implies that concentrator solar collectors should be symmetrically truncated to maximize the energy yield (Adsten et al., 2005). In order to follow the solar radiation profile, design concepts with symmetric truncated CPC and parabolic non-tracking trough geometries with vertical bifacial receivers have been developed.

An evaluation of the electrical and thermal performance of two symmetrical concentrating trough geometries, such as Pure Parabola (PP) and CPC is presented. These geometries were designed with the aim of lowering the shadowing effect on the PV arrays, as well as reducing the cost of solar systems, by using cheap reflectors to replace the PV cells.

Several sets of ray-tracing simulations were performed in order to get the Incidence Angle Modifier (IAM) for each geometry. The data was then fed into a multi-paradigm numerical computing software (MATLAB) in order to get the IAMs. A thermal performance model based on the international standard ISO 9806:2013 and an electrical performance model suggested by Lämmle et al. (2017), have been implemented to estimate the electrical and thermal performance of the design concepts.

1.1. Compound parabolic collectors

Solar energy technologies, as any energy technologies, aim at providing energy at the lowest possible cost. This can be accomplished by increasing the efficiency of the systems or by decreasing the investment cost, and at the same time reduces the installation ground area (Perers and Karlsson, 1993). Concentrating solar collectors re-direct the solar radiation (both beam and diffuse radiation) that passes through an aperture into the receiver over ranges of incidence angles within wide limits (thus defining the acceptance half-angle, θ_c). For systems of low concentration ratio, part of the diffuse radiation will be reflected into the receiver, with the amount depending on the acceptance angle of the concentrator (Duffie and Beckman, 2013).

Compound Parabolic Collectors (CPC) are non-imaging concentrators that do not require a tracking system due to the ability to reflect the available beam radiation and partly diffuse radiation to the receiver. According to Rabl et al. (1980), CPC reflectors can have different configurations, such as (i) flat one-sided absorber, as in Fig. 1; (ii) flat two-sided (fin) absorber (used in this paper), as in Figs. 4 and 5; (iii) tubular absorber and (iv) wedge absorber. CPCs combine two parabolic reflectors (symmetric or asymmetric), each one of them with its own focus at the lower edge of the other parabola.

Duffie and Beckman (2013) described the relation between the size of the aperture (2a) and the size of the receiver (2a′) as the concentration ratio (known as the ratio between the aperture area and the

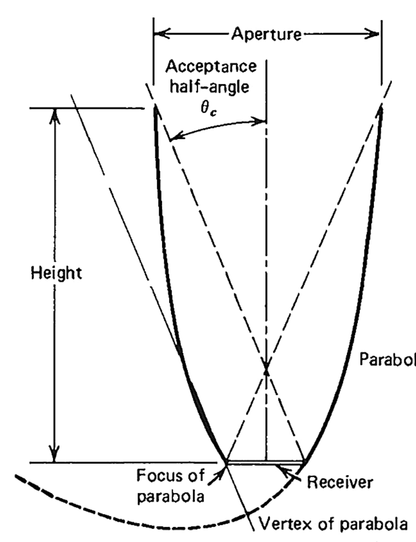

Fig. 1. Cross section view of a symmetrical non-truncated one-sided absorber CPC (Duffie and Beckman, 2013).