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Outdoor performance of a low-concentrated photovoltaic–thermal hybrid system with crystalline silicon solar cells

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HIGHLIGHTS

- Four different weather conditions are considered and characterized.
- The concentrator is carefully designed to get a uniformly concentrated irradiation.
- A model is made to evaluate the system with optical efficiency of concentrators considered.
- Direct and diffuse lights are distinguished in the model.

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ABSTRACT

The main problem of the photovoltaic system is the high cost of solar cells. One possible solution is to concentrate the solar radiation to minimize the required cell area for the same output. In this paper a low-concentrating photovoltaic–thermal hybrid (PV/T) system was set up to study the electrical and thermal outputs under different weather conditions. The concentrator in the system was designed using Fresnel lens and flat mirrors to get a uniformly concentrated irradiation on the solar cells. The results show that on a clear day the electrical efficiency is about 10% and the thermal efficiency is about 56% for our system. Irradiance is the most important factor to characterize the weather. When the irradiance is above 350 W/m^2 the electrical output will saturate and when it is above 162 W/m^2 the thermal energy can be effectively output in our system. The system is also modeled to predict the output and describe the concentrator's performance. By this model different concentrated PV/T systems can be compared in the electrical and thermal outputs and also the performance of concentrators.

1. Introduction

Photovoltaic power is a clean energy which is directly transformed from solar energy. It is regarded as an important potential alternative to the traditional power to solve the environmental problem. However, the cost of the photovoltaic is still too high to compete with the traditional power. The main cost of the photovoltaic is from the solar cell, so one possible method to reduce the cost is to concentrate the radiation to minimize the required cell area for the same output. But solely concentrating the radiation will increase the cell's temperature. Some cooling method is needed to lower the cell temperature, prevent thermal damage and maintain cell efficiency [1]. A concentrating photovoltaic/thermal hybrid (CPV/T) system is a hybrid photovoltaic and thermal power generation system [2] which produces both electricity and heat to increase the overall efficiency. The high concentrated system usually needs a dual-axis tracking system and an efficient heat removal mechanism and is very complex. Therefore the low concentrated PV/T systems with water or air as cooler are usually chosen for their simple structure and high stability.

A significant amount of research and development work on CPV/T technology has been conducted, including concentrator designing, performance evaluation and system optimization. One key component for the CPV/T system is the concentrator which affects the distribution of solar radiation on the absorber surface and the temperature profiles directly. Reflectors such as compound parabolic concentrator type (CPC) [3,4], parabolic type [5,6], flat type [7–9], linear Fresnel type [10] have been designed and studied to increase the thermal and electrical output. Brogren et al. [3] studied the optical efficiency of a PV/T CPC system and found that the optical efficiency depended on the properties of the glazing, reflector and absorber. The optical efficiency of CPC was also determined to be 0.71. Kribus et al. [11] designed a miniature concentrating PV/T system and analyzed the heat transport system, the electric and thermal performance, the manufacturing cost and the resulting cost of energy in case of domestic water heating.

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Nomenclature

A	surface area (m^2)
A_{in}	incident area of the concentrator (m^2)
a, b, c, C	constants
CPC	compound parabolic concentrator
c_p	specific heat at constant pressure (J/kg K)
DAS	data acquisition system
F	view factor
FF	fill factor (%)
G	irradiance (W/m^2)
H	daily insolation (J/m^2)
H_{cotton}	effective thickness of the thermal insulation cotton (m)
I_{sc}	short circuit current (A)
k_1	optical efficiency for direct solar radiation
k_2	optical efficiency for diffuse solar radiation
k_3	constant to describe the non-uniform effect of irradiance
L	the length of the receiver (m)
Nu	Nusselt number
NOCT	normal operating cell temperature
PV/T	photovoltaic–thermal hybrid
P_{in}	power of incident light (W)
P_{out}	power of lost light (reflected or scattered) (W)
P_e	electrical output (W)
P_{th}	thermal output (W)
P_{lost}	lost heat (W)
p_i	subpart of lost heat (W)
Pr	Prantdl number
Q	volume flow rate (m^3/s)
Re	Reynolds number
Ra	Rayleigh number
RMSE	Root-Mean-Square-Error
STC	standard testing condition
T	temperature (°C)
T_{in}	flow temperature of the inlet (°C)
T_{out}	flow temperature of the outlet (°C)
T_{flow}	average temperature of the flow (°C)
V_{oc}	open circuit voltage (V)
W	the width of the receiver (m)
Greek symbol	
λ	heat conductivity (W/m K)
ε	emissivity
σ	Boltzmann constant (W/m K)
φ	the angle of inclination from the horizontal (°)
η	efficiency
ρ	density of water (kg/m^3)
Subscript	
d	diffuse
t	total
i	series number
a	ambient
rad	heat radiation
c	solar cell
eff	effective
cr	critical
ref	reference

Mittelman et al. [12] proposed a CPV/T system to produce electrical and high grade thermal energy and gave some detailed analysis. Tripanagnostopoulos [13] did lots of work to improve the performance of CPV/T systems at the University of Patras. The effect of glass cover, different collector designs and cooling methods had been presented. But their systems are mainly to be combined with buildings. Li et al. [2] investigated the performance of four kinds of solar cells under different irradiance intensities on a Trough CPV/T system and found that different kinds of solar cells should have their own optimum concentration ratios. The optimum concentration ratio of the single crystalline silicon cell is 4.23.

The accurate prediction of performance was conducted with complex mathematical models. Chow [14] developed a dynamic model to predict the transient performance of thermal/electrical output and efficiencies. Bernardo et al. [1] also used a dynamic model to evaluate the performance of a low concentrating PV/T system in Sweden. Zondag et al. [15] proposed dynamic 3D and steady state models for PV/T prototypes. Lu and Yao [16] paid more attention on the solar cell structure and developed an optical model for arbitrary layers to evaluate the energy allocation of a PV system.

Up to now most researches and developments are related to the new designs and optimization of systems, but the performances under different weather conditions are rarely analyzed. The weather condition is always considered to be clear in most references. A better understanding of the weather effect and evaluating the output under different weather conditions are needed. The purposes of this article are to (1) characterize the weather and compare the system performances under different weather conditions and (2) model the system with a simple method.

Firstly a low-concentrated PV/T system was set up. In the system a compound concentrator with Fresnel lens and flat mirrors is designed (Section 2). Then the thermal and electrical performances under different weather conditions are measured and analyzed (Sections 4.1, 4.2 and 4.3). In the end the system is modeled to predict the output under different weather conditions (Sections 3 and 4.4).

2. Experimental setup

The sketch and the photograph of a low-concentrated PV/T system are shown in Fig. 1. The experimental setup is located on the roof of a building in Tsinghua University at 39°59′59.46″N and 116°19′09.04″E. The system mainly includes three parts, i.e. the concentrator and PV/T component (including the receiver and the solar module), the water circulation system and the data acquisition system (DAS).

The concentrator was designed with consideration of concentration ratio and irradiance uniformity. Li et al. [2] found that the concentrated PV/T system using single crystalline silicon solar cells had an optimal concentration ratio of 4.23. The indoor experiment by Shaltout et al. [17] also showed that the optimum concentration ratio for Si solar cell was around 4. Assuming an optical efficiency of 80% the theoretical concentration ratio of the designed concentrator should be about 5 to reach an optimal efficiency. The irradiance uniformity also impacts the cell's performance. Simulation with light tracing method indicated that two parallel plane mirrors were helpful to uniformize the radiation on the solar cells. Thus the concentrator was made with Fresnel lens and two flat mirrors to get an optimal concentration ratio and uniform irradiance, shown in Fig. 2. The incident area and exit area of the concentrator are $600 \times 400\ mm^2$ and $600 \times 70\ mm^2$, respectively.

The solar module which includes 18 pieces of series-connected solar cells is pasted on an aluminum receiver by thermal conductivity silica gel. The parameters of the solar module at STC are listed in Table 1. The receiver is insulated on the back and sides