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Numerical analysis of a multi-channel active cooling system for densely packed concentrating photovoltaic cells

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ABSTRACT

The efficiency of concentrating photovoltaic cells (CPVs) is highly affected by the cell temperature. The main problems for the cooling devices are insufficient heat dissipation and uneven heat distribution. In this study, a novel cooling manifold with multi-channels for densely packed CPVs were proposed and numerical investigated. The effects of coolant type, inlet flow rate and channel dimensions on the cooling performance of the manifold heat sink device were examined. The influence of solar irradiance was also investigated at four solar terms in Shenzhen, China. The results show that great cooling performance and temperature distribution uniformity can be achieved by the novel cooling manifold. Thermal resistance of the studied manifold is also lower than those reported in the literature.

1. Introduction

With the development of economy and technology around the world, the global energy consumption increases significantly year by year [1]. Most energy consumption is based on fossil fuels, but fossil fuels have great pollutant emissions to the environment [1,2]. As the most abundant renewable energy source, solar energy has the potential to replace fossil fuels in the future [1,2]. The total global primary energy supply in 2014 is 13,699 Mtoe (574 EJ), meanwhile, the estimated total annual solar energy potential ranges from 1575 EJ to 49,837 EJ which is about 2.7–86.8 times of the total primary energy supply [3,4]. Thermal and electrical energy converted from the irradiance are the most common applications of solar energy [5].

Solar photovoltaic (PV) can convert solar energy into electricity directly by using photovoltaic effect of semiconducting materials. And the concentrating PV (CPV) is one kind of solar PV which uses cheap optical devices such as Fresnel lenses, parabolic dish reflectors, parabolic trough reflectors, compound parabolic concentrators and central receiver systems combining with suitable technologies to concentrate the sun irradiance on small PV cells so as to reduce the cost and improve the efficiency comparing with the normal non-concentrator PV systems [6,7]. Solar Cell Efficiency Tables [8] reported that non-concentrated PVs in general have an efficiency less than 25%, whereas the CPVs have much higher efficiencies. A new world efficiency record of a four-junction CPV is up to 46%, which was developed by Soitec and CEA-Leti, together with the Fraunhofer ISE and conformed by AIST in Japan [9]. Depending on concentrator geometry, concentrators can be sorted into single cell, linear geometry and densely packed modules.

In a CPV system, only a fraction of the sunlight arriving the surface of the PV cells is converted into electricity, and the remaining solar energy converts into heat [10]. The temperature on the PV cells can increase significantly without cooling because of the photon-matter interactions [11,12]. Excessive heat can not only reduce the efficiency of the PV cells, but also cause irreversible structural damages such as deformation, delamination and micro-cracks because of the thermal stress [13–15]. Aldossary et al. [16] confirmed by numerical simulation that the temperature on the cell with an efficiency of 41.2% and a concentration ratio of 500 can reach 922.72 K without heat sink. In addition, non-uniform temperature distribution on the surface of concentrated PV cells also leads to decreased efficiency and damaged structure, particularly in the cases with high concentration ratios [13,17,18]. Therefore, it is necessary to introduce effective cooling methods to dissipate heat and maintain the uniform temperature distribution on the cell.

Micheli et al. [14] classified the cooling methods for CPV into active cooling and passive cooling according to their cooling mechanism. The passive cooling methods mainly include planar plates [19,20], finned metal strips [16,21] and heat pipes [22,23]. Passive cooling methods

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Nomenclature

Symbol

DNI	direct normal irradiance, W/m^2
$\bar{I}_D$	mean DNI, W/m^2
I_D	transient DNI, W/m^2
Δt	time segment, h
q	heat per unit area, W/m^2
q_s	heat, W
q_{in}	DNI received by CPV cells, W/m^2
q_c	heat loss due to the convection, W
q_r	heat lost by radiation, W
q_e	electrical output, W
q_{cool}	heat removed by the cooling system, W
η_{cell}	electrical efficiency
η_{ref}	typical electrical efficiency
η_{conc}	optical efficiency
CR	concentration ratio
β	thermal coefficient, K^{-1}
T_{ref}	reference temperature, K
T_{cell}	temperature of CPV cells, K
T_w	average surface temperature
T_a	ambient temperature
A	solar irradiated area, m^2
A_c	convection area, m^2
A_r	radiation area, m^2
l	characteristic dimension, m
h	convection heat transfer coefficient, W/(m^2·K)
ε	emissivity
σ	Stefan–Boltzmann constant, W/(m^2·K^4)
λ	thermal conductivity, W/(m·K)
Nu	Nusselt number
Pr	Prandtl number
u_{wind}	wind velocity, m/s
ρ	density, kg/m^3
μ	kinetic viscosity, Pa·s
SGM	single-group manifolds
DGM	double-group manifolds
USC	upper surface of the cell array
USCP	upper surface of the copper plate
LSCP	lower surface of the copper plate
SE	Spring equinox
SS	Summer solstice
AE	Autumn equinox
WS	Winter solstice
RDV	relative difference of velocity
RTD	relative temperature difference
i	outlet number
V_i	velocity at the ith outlet, m/s
V_i'	velocity at the ith outlet, m/s
T_{ext}	average temperature, K
T_{gc}	average temperature, K
W_{pump}	pumping power, W
V_f	volumetric flow rate, m^3/s
ΔP	pressure loss, Pa
η_p	pump efficiency
η_m	motor efficiency

Subscripts

D	direct
ref	reference
conc	concentration
c	convection
r	radiation
e	electrical
cool	cooling system
w	wall
a	ambient
wind	wind velocity
ext	extra-fine
gc	grid number class
p	pump
m	motor

are generally more reliable and cost effective than active cooling methods. However, active cooling shows much higher cooling performance than passive cooling [16]. Royne et al. [13] pointed out that both passive and active cooling methods could be used to dissipate heat from the CPV for single cell systems. However, only active cooling methods are suitable for cooling of densely packed cells with a high concentration ratio.

A lot of works has been done in order to achieve better heat dissipation using active cooling in a CPV system. Both direct liquid-immersion cooling [24,25] and jet impingement cooling [26] were studied for CPV systems. Drawback of the liquid-immersion cooling is that incident light can be absorbed by the liquid layer [27]. The inherent disadvantage of the jet impinging cooling is the non-uniform heat transfer coefficient in the radial direction which causes temperature variations on the surface of the cell array [26]. Cooling using manifolds with channels is another effective active cooling method. Lasich [28] patented a water cooling circuit for heat dissipation of an array of 1536 closely packed rectangular PV cells. The cooling circuit could extract heat up to 50 W/cm^2 from the cells, and have the ability to maintain the temperature of the cells less than 313.15 K. Teo et al. [29] presented an experimental study for uniform airflow distribution and heat dissipation using a parallel array of ducts with inlet/outlet manifold attached to the back of a PV array. The effect of air flow rate on the performance of the PV array was investigated. This cooling device could lead to an increase in efficiency of cells from 8–9% to 12–14%. A system simulation was described by Kerzmann et al. [30], in which a linear CPV system with a concentration ratio of 80 and an active channel cooling system was introduced. It could not only generate electricity, but also act as a system that recovered the heat energy. Du et al. [31] used an aluminum water-cooling pipe to dissipate heat from a CPV solar cell module. The effect of water flow rate on the cooling performance was studied. And the result show that the operating temperature of the CPV module could be reduced to below 333.15 K. Sabry [32] presented a system consisting of four CPV cells of linear arrangement contacted with a tube flowing coolant water on the top surface. The effects of flow rate, tube internal diameter and convective heat transfer on heat dissipation across the cells were investigated by employing the CFD simulation technique. The first cell near the inlet could be effectively cooled, whereas the fourth cell near the outlet still had high temperature due to the increase of coolant water temperature. Aldossary et al. [16] investigated an active water cooling channel for CPV cells at 500 suns. The channel with a water flow rate of 0.01 m/s had the ability to reduce the cell temperature to be around 333.15 K. Moreover, the water outlet temperature could rise to 363.15 K when there were 14 cells placed along the channel linearly. Ramos-Alvarado et al. [33] compared the cooling performances for a heat surface among manifolds with serpentine channel, two type parallel channels, T-shape channel, and modified channels. The authors showed that a maldistributed flow often led to a decrease of the heat sink efficiency due to local high temperature, which induced adverse effect on the pressure drop across

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