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Performance study of water-cooled multiple-channel heat sinks in the application of ultra-high concentrator photovoltaic system

Woei-Chong Tan [a], Kok-Keong Chong [a,*], Ming-Hui Tan [b]

[a] Lee Kong Chian Faculty of Engineering and Science, Universiti Tunku Abdul Rahman, Jalan Sungai Long, Bandar Sungai Long, 43000 Kajang, Selangor, Malaysia
[b] Department of Industrial Engineering, Faculty of Engineering and Green Technology, Universiti Tunku Abdul Rahman Kampar Campus, Jalan Universiti, 31900 Kampar, Perak, Malaysia

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ABSTRACT

For achieving cost effectiveness in solar power generation, ultra-high concentrator photovoltaic (UHCPV) system operating at 1800 suns is highly recommended in order to minimize the usage of semiconductor material. Although sunlight focusing can be accomplished via two-stage concentrator consisted of non-imaging dish concentrator and an array of crossed compound parabolic concentrator lenses, the thermal management of concentrator photovoltaic (CPV) cells remains as a crucial problem. The objective of this study is to optimize the configuration of multiple-channel heat sink with the best design in thermal performance so that the temperatures of CPV cells are below 100 °C even operating under ultra-high concentrated sunlight. Comprehensive analysis has been carried out via computational fluid dynamics (CFD) simulation to study thermal performance of heat sinks for different configurations with various fin thicknesses and fin heights. To emulate the real case, optical analysis has been carried out via ray-tracing method to simulate the solar flux distribution and input solar power illuminated on receiver so that the results can be fed into the CFD modeling. The heat sink with configuration of 1 mm fin thickness × 20 mm fin height (1 × 20) was found to be the most optimized design in which the CFD simulation has shown the lowest values for both average temperature of CPV cells and maximum temperature difference between CPV cells. By optimizing the average water velocity at 0.6 m/s, the heat sink with the configuration of 1 × 20 can maintain the CPV cells operating at 91.4 °C under solar concentrator ratio of 1800 suns and direct normal irradiance of 1000 W/m^2. Through the optimization of the thermal performance, the UHCPV system can produce the net electrical output power of 4064 W at power conversion efficiency of 31.8%.

1. Introduction

In recent decades, effective cooling system with safe and high efficient operation is a necessary component for high-heat-releasing system such as high-heat-releasing electronic device, high power light-emitting diode, fuel cell power source and high concentrator photovoltaic (HCPV) system (Baig et al., 2012; Fernández et al., 2014; Jakhar et al., 2016; Kandlikar and Lu, 2009; Pandiyan et al., 2008; Scholta et al., 2009; Wadsworth and Mudawar, 1990). To reduce the cost of solar power generation, HCPV system with high solar concentration ratio (SCR) illuminated on the concentrator photovoltaic (CPV) cells can permit higher power conversion efficiency and minimize the utilization of expensive solar cell material. The drawback of high SCR is that the temperatures of CPV cells will increase in a rapid rate even higher than the recommended operating temperature of the cells if inappropriate heat dissipating system is applied and hence it can deteriorate power conversion efficiency dramatically (Dalal and Moore, 1977; Luque, 1989; Mbewe et al., 1985; Royne and Dey, 2007). To achieve cost effectiveness in solar power generation, ultra-high concentrator photovoltaic (UHCPV) system with SCR of more than 1000 suns is proposed to significantly reduce the usage of CPV cells (Algaro and Rey-Stolle, 2012). The introduction of UHCPV system has elevated the potential of solar power generation towards more economically competitive comparing to the conventional source of energy and can emerge as an important alternative power source in the future. For ultra-high solar flux concentrated on the CPV cells, thermal management of UHCPV system becomes a crucial issue in order to maintain the CPV cells at acceptable operating temperature.

* Corresponding author.
E-mail addresses: chongkk@utar.edu.my, kokkeong_c@yahoo.com (K.-K. Chong).

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Nomenclature

$A_{c\text{-}cha}$	cross sectional area of each channel in heat sink, m^2
A_{illu}	area illuminated by concentrated solar flux, m^2
DNI	direct normal irradiance, W/m^2
E	internal energy, J
$\dot{m}_{in}$	total inlet mass flow rate, kg/s
N_{cha}	total number of channels in heat sink
N_{CPV}	total number of CPV cells.
$\%\Delta p$	uncertainty of pressure drop, %
$\%\Delta T_{i\text{-}o}$	uncertainty of temperature difference of water from inlet to outlet of heat sink, %
P	pressure, Pa
P_{out}	electrical power output of CPV cell, W
P_{net}	net power of the UHCPV system, W
P_{pump}	pumping power across heat sink, W
P_{sol}	input solar power, W
S	source of power per unit volume, W/m^3
SCR	solar concentration ratio, suns
SCR_{avg}	average solar concentration ratio, suns
T_{CPV}	temperature of CPV cell, °C
$T_{CPV\text{-}avg}$	average temperature of CPV cells, °C
$T_{CPV\text{-}max}$	maximum temperature of CPV cells, °C
$T_{CPV\text{-}min}$	minimum temperature of CPV cells, °C
T_{in}	water inlet temperature, °C
u	velocity in x-direction, m/s
u_w	average water velocity in heat sink, m/s
v	velocity in y-direction, m/s
w	velocity in z-direction, m/s
x	x-direction
y	y-direction
z	z-direction

Greeks symbols

Δp	pressure drop across heat sink, Pa
$\Delta p_{ex\text{-}fine}$	pressure drop across heat sink for extra fine mesh level, Pa
$\Delta p_{non\text{-}ex\text{-}fine}$	pressure drop across heat sink for non-extra fine mesh level, Pa
$\Delta T_{i\text{-}o\text{-}(ex\text{-}fine)}$	temperature difference of water from inlet to outlet of heat sink for extra fine mesh level, °C
$\Delta T_{i\text{-}o\text{-}(non\text{-}ex\text{-}fine)}$	temperature difference of water from inlet to outlet of heat sink for non-extra fine mesh level, °C
ΔT_{CPV}	maximum temperature difference between CPV cells, °C
η_{pump}	pump efficiency, %
ρ	water density, kg/m^3

To date, there are numerous studies regarding the consequences of the CPV cells illuminated under high SCR. Braun et al. (2011) utilized a flash-like, real sun optical system to study the performance of CPV cell illuminated under SCR ranging from 12 to 8600 suns within a period of 1.5 ms. Despite open circuit voltage (V_{oc}) increasing proportional to the SCR, it is inversely proportional to the CPV cell temperature and thus deteriorates the power conversion efficiency. The effect of cell heating was found to become non-negligible at concentration levels approaching 1000 suns even as short as a few milliseconds and they have concluded that it is importance to have heat rejection strategies in CPV system. In year 2009, Cui et al. experienced that a single CPV cell without heat sink can reach an extreme-high temperature of 1200 °C at SCR of 400 suns and the temperature of CPV cell was reduced dramatically by just attaching a cooling panel onto it. According to Araki et al. (2002), the CPV cell without heat sink can be heated up to 1400 °C at SCR of 500 suns. It has been proven that heat sink is an inevitable component for HCPV system. As a result, a reliable and high thermal performance heat sink is a necessary for cooling a CPV cell to its recommended operating temperature for preventing the CPV cell from unrecoverable damage as well as preserving the power conversion efficiency at optimized operating condition (Royne et al., 2005).

Araki et al. (2002) have studied the temperature rise of CPV cell under illumination of 500 suns at direct normal irradiance (DNI) of less than 700 W/m^2 by using Fresnel lens. In the experiment, a heat spreading aluminum plate attached to the CPV cell is used as heat sink and it is cooled by natural convection. The temperature rise of the CPV is 18 °C above the ambient temperature while the ambient temperature was not stated. Micheli et al. (2015a) have compared the thermal performance between micro-finned silicon heat sink and flat silicon heat sink to cool down a CPV cell under SCR of 500 suns & DNI of 1000 W/m^2 via natural convection in the Fresnel lens HCPV system. Both micro-finned and flat heat sinks were studied under two conditions: the operating condition by considering power conversion efficiency of CPV cell as 42.5% and the worst case condition by considering power conversion efficiency of CPV as 0%. For this study, the maximum CPV cell temperatures for micro-finned heat sink and flat heat sink are 70.4 °C and 78.8 °C respectively under operating condition, while they are 99.9 °C and 111 °C respectively under worst case condition. In the same year, Micheli et al. (2015b) have designed a passive cooling finned heat sink for the application of UHCPV system by deploying the least-material approach to minimize the weight whilst maximizing the thermal performance of heat sink. From the simulation, an aluminum heat sink with eight units of 6 cm high fins on 11 cm × 11 cm base is capable to maintain a CPV cell with a dimension of 3 mm × 3 mm at the temperatures of 63.3 °C and 91.5 °C under operating condition and worst case condition respectively provided that SCR is 4000 suns at DNI of 900 W/m^2.

In southern Italy, Renno and Petito (2013) have introduced a domestic used hybrid photovoltaic and thermal system (CPV/T) consisted of two concentrators: Fresnel lenses and parabolic mirrors fixed on a two-axis sun tracker and CPV cells attached to cooling plate. With the SCR achieved by the hybrid CPV/T system ranging 600–900 suns, the maximum water temperature was recorded as 90 °C for the mass flow rate of water ranging from 50 to 200 kg/h but the CPV cell temperature was not stated in their work. Kermani et al. (2009) have investigated the heat transfer performance of a manifold micro-channel heat sink in application of CPV system. They replaced the solar concentrator by a heater with heat flux of 75 W/cm^2 that corresponded to SCR of 1000 suns by assuming power conversion efficiency of 25%. The mass flow rate of the system was recorded as 0.0011 kg/s and the heat transfer coefficient was obtained as 65,480 W/m^2 K. Xu et al. (2015) studied the outdoor performance of a 1090 suns hybrid photovoltaic and thermal system (CPV/T) using Fresnel (primary) and optical prism (secondary) as concentrators and aluminum plate heat sink with grooved tube as cooling system. The system was tested outdoor with the ambient temperature varying from 15 °C to 17 °C and DNI ranging from 300 W/m^2 to 700 W/m^2. With the water flow rate of 0.33 m^3/h, the CPV cell temperature changed in the range between 60 °C and 90 °C owing to the variation of DNI throughout the experiment and the water temperature was raised from 25 °C to 55 °C during daily data collection.