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Thermal management of concentrator photovoltaic systems using microchannel heat sink with nanofluids

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ABSTRACT

A new cooling method for concentrator photovoltaic system is proposed using wide microchannel heat sink with nanofluids. A comprehensive three-dimensional model is developed. The model couples the two-phase (Eulerian-Eulerian) multiphase model for the conjugate heat transfer of nanofluid flow in a wide microchannel heat sink with the thermal model of the concentrator photovoltaic systems. The model is numerically simulated and validated with the available experimental and numerical data. The influences of nanoparticle types, volume fractions, and coolant flow Reynolds number on the solar cell performance parameters are investigated. Results indicate that using SiC-water nanofluids attains lower cell temperature compared with Al_2O_3-water nanofluids. The increase of nanoparticles volume fraction ratio remarkably reduces the solar cell temperature and enhances the cell temperature uniformity and electrical efficiency. Furthermore, increasing the flow Reynolds number to a specific value significantly enhances the net electrical power. Further increase of the Reynolds number results in a significant reduction in the cell net gained power. By using 4% SiC-water nanofluid, the reduction in maximum local solar cell temperature is ranged between 8 °C and 3 °C compared with pure water with changing the flow Reynolds number from 12.5 to 250 at solar concentration ratio of 20.

1. Introduction

Thermal management of concentrator photovoltaic (CPV) systems is an essential issue in low and high concentration ratio (CR) systems (Royne et al., 2005). In such systems, the overall performance of the solar cells is strongly affected by the working temperature (Sathe and Dhoble, 2017). Recently, the highest confirmed polycrystalline solar cell efficiencies are presented and summarized by (Martin et al., 2017). Based on their review, the maximum obtained electrical efficiency of polycrystalline silicon solar cells is 22.3 ± 0.4% at AM1.5 spectrum (1000 W/m^2), and 25 °C. However, when the temperature of the cell is above the standard operating temperature, the solar cell electrical efficiency is expected to decrease by nearly 0.4–0.65% per one degree rise of cell temperature (Ma et al., 2015). The remaining part of the incident solar irradiance is absorbed in the cell causing a significant rise in the cell temperature (Agrawal et al., 2011; Emam et al., 2017; Radwan et al., 2018a). In addition, temperature non-uniformity significantly reduces the CPV system performance due to a loss in the cell output power and induces thermal fatigue due to a large amount of thermal stresses. This might cause irreversible damage to the silicon wafer because of the excess localized heating or hot spots (Al-Amri and Mallick, 2014). In linear Fresnel lens solar concentrators, solar irradiance is concentrated on series connected cells. These series connection exhibit higher damage as the current directly varies with light intensity, so the gained current will be restricted by the cell with the maximum temperature. This failure is defined as the current matching problem (Ahmed and Radwan, 2017; Bahaidarah, 2016; Radwan et al., 2018b). This problem can be avoided by keeping a uniform temperature across the solar cell. Therefore, the better overall performance of the CPV systems can be attained by optimizing the use of solar energy with uniform and low average temperature of the silicon wafer to avoid hotspot and current mismatching problem. Thus, thermal regulation of CPV systems is of great importance.

Utilizing hybrid micro-channel photovoltaic thermal systems was comprehensively investigated by Agrawal and Tiwari (2011), Agrawal et al. (2015), and Rajoria et al. (2015). In these works, comprehensive thermal models including exergy, energy, and enviro-economic analysis were developed. However, pure water was examined in several researches to cool the PV system and results showed a temperature variation along the surface of CPV string especially for simple conventional

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Nomenclature

A	solar cell area [m^2]
C	specific heat of cooling fluid [J/kg·K]
D_h	hydraulic diameter [m]
G	net concentrated solar radiation [W/m^2]
H	microchannel height [m]
k	thermal conductivity [W/m·K]
L	microchannel length and solar cell length [m]
$\dot{m}$	cooling fluid mass flow rate [kg/s]
P	pressure [Pa], electrical, friction and net power [W]
Re	Reynolds number
T	temperature [°C]
u	velocity component in x-direction [m/s]
V	velocity vector [m/s]
V_w	wind velocity [m/s]
W	width of the channel and width of the solar cell [m]

Greek symbols

η	solar cell electrical efficiency and CPV/T system thermal efficiency
μ	fluid viscosity [Pa·s]
α	absorptivity
β	cell temperature coefficient [1/K]
δ	thickness [m]
ε	emissivity
ρ	fluid density [kg/m^3]
σ	Stephan-Boltzmann constant $5.67 * 10^{-8}$ [W/(m^2·K^4)]
τ	transmissivity

Subscripts

a	ambient
ch	channel
conv, g-a	convection loss from glass to ambient
el	electrical
Fric.	friction
g	glass
in	inlet
int	interval part of EVA
l	liquid phase
net	net
p	solid (particle) phase
rad, g-s	radiation loss from glass to sky temperature
ref	reference condition, G = 1000 w/m^2, T = 25 °C
s	solid phase and sky
sc	silicon layer
th	thermal

heat sink designs (Yang and Zuo, 2015). The use of nanofluids as coolant medium has been experimentally and numerically investigated in the applications of photovoltaic thermal (PV/T) systems (Al-Waeli et al., 2017). Most of these studies indicated that using nanomaterials as a dispersed phase in the base fluid could enhance its thermo-physical properties of the coolant and consequently improve the coolant ability for heat removal. It was reported that the energy cost from the PV/T system using silver (Ag) –water nanofluids with volume fraction of 0.5% is 82% less than the domestic price of electricity. Moreover, the PV/T system could prevent the release of 16,974.57 tons of CO_2 into the atmosphere (Lari and Sahin, 2017). The techno-economic assessment of grid connected PV/T system using Silver–water nanofluids has been investigated based on theoretical and experimental work existing in (Al-Waeli et al., 2018). They concluded that grid connected PV/T system with nanofluid improved the PV technical and economic performance. In the present work, the used nanoparticles such as aluminum oxide (Al_2O_3) and silicon carbide (SiC) are cheaper than Silver. Accordingly, the used nanofluid is more economical compared with the previous work.

Some of the recent nanofluid modeling techniques used one-dimensional, two-dimensional, and three-dimensional thermal model. In one-dimensional model, the photovoltaic module temperature changes only with thickness and the cell temperature uniformity cannot be predicted. One further step toward developing a more accurate thermal model for the PV/T system was conducted by developing two-dimensional analysis. Xu and Kleinstreuer (2014a, 2014b) developed a two-dimensional thermal model for concentrated photovoltaic thermal (CPV/T) systems for crystalline silicon at CR of 200 Suns. In their model, the turbulent single-phase model is developed to investigate the performance of Al_2O_3-water nanofluid as a coolant with channel height ranges from 2 mm to 14 mm. At *Re* of 3000 and channel height of 10 mm, they concluded that the solar cell electrical efficiency improved with the increase in the nanoparticle volume fraction. It was found that the cell electrical efficiency increases from 16.83% to 17.12% for pure water and 4% Al_2O_3-water nanofluid, respectively. The same group used the same two-dimensional thermal model to compare the performance of the generic polycrystalline silicon solar cell with the multi-junction solar cell (Xu and Kleinstreuer, 2014a, 2014b). They concluded that using nanofluids is not an efficient coolant for the concentrated multi-junction solar cell/thermal systems. Recently, Rejeb et al.(2016) developed a two-dimensional thermal modeling of the PV/T system using Al_2O_3-water and Cu-water nanofluids as coolants with nanoparticle loading ranges from 0% up to 0.4% wt. dispersed in different base fluids such as water, and ethylene glycol. They recommended using water rather than ethylene glycol for the thermal management of the PV systems. In addition, they reported that using Cu-water nanofluid attains a higher electrical and thermal efficiency in comparison with Al_2O_3-water nanofluid at the same nanoparticles loading ratio. It is known that the two-dimensional thermal model correctly predicts the thermal behavior of conventional thermal absorbers when the change in the third dimension could be insignificant (Siddiqui and Arif, 2013). However, in irregular configurations where the temperature variation in the third dimension is a major, the two-dimensional modeling cannot be used to predict the precise behavior of the PVT systems (Zondag et al., 2002).

To overcome the limitations associated with one- and two-dimensional models of the PV/T systems, it was reported that the three-dimensional model is more flexible and can be easily adapted to investigate the performance of complicated heat sink designs. At the same time, such model can handle the patterns of complex thermal absorber designs with a high level of accuracy (Zondag et al., 2002). One of the essential parameters that can be extracted using three-dimensional model is the solar cell temperature uniformity. It was found that the cell efficiency declines because of the cell non-uniform temperature distribution that causes a reverse saturation current (Domenech-Garret, 2011) and current mismatching problems (Bahaidarah, 2016). Moreover, thermal expansion depends on the local cell temperature, and the non-uniformity of cell temperature causes a mechanical stress and reduces the lifetime of solar cells (Royne et al., 2005). Therefore, the three-dimensional model will greatly assist in predicting the temperature distribution, and consequently, the temperature uniformity of a solar cell can be accurately estimated. Khanjari et al.(2016) numerically investigated the use of pure water and two different types of nanofluids Alumina-water and Ag-water nanofluids with volume fraction up to 12%. They found that increasing the inlet coolant velocity enhances the rate of heat dissipation from the PV panel and the heat transfer rate