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Performance enhancement of concentrated photovoltaic systems using a microchannel heat sink with nanofluids

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ABSTRACT

A new cooling technique for low concentrated photovoltaic–thermal (LCPV/T) systems is developed using a microchannel heat sink with nanofluids. In this study, Aluminum Oxide (Al_2O_3)–water and Silicon Carbide (SiC)–water nanofluids with different volume fractions are used as cooling mediums. The influence of cooling mass flow rate and nanoparticles volume fractions on the performance of LCPV/T system is investigated at different values of concentration ratio. A comprehensive model is developed which includes a thermal model for the photovoltaic layers, coupled with thermo-fluid dynamics of two-phase flow model of the microchannel heat sink. The model is numerically simulated to estimate the performance parameters such as the solar cell temperature and the electrical and thermal efficiency. Results indicate that a significant reduction in solar cell temperature is attained particularly at the high concentration ratio by using nanofluids compared to using water. Using SiC–water nanofluid achieves a relatively higher reduction in cell temperature than Al_2O_3–water nanofluid. By increasing the volume fraction of nanoparticles, both SiC–water and Al_2O_3–water nanofluids accomplish a major reduction of cell temperature. As a result, the use of nanofluids achieves higher solar cell electrical efficiency, particularly at lower Reynolds number (Re) and higher concentration ratio, than the use of water. The influence of nanofluids on thermal efficiency varies according to the concentration ratio. Furthermore, friction power increases with the increase in both Reynolds number and nanoparticle volume fraction. By increasing the volume fraction of the nanoparticle, the net electrical power increases at high concentration ratio while the thermal power decreases. The results of this study indicate that the use of nanofluids is effective cooling technique, particularly at high solar concentration ratios where the solar cell temperature reduces to 38 °C, and electrical efficiency improves up to 19%.

1. Introduction

Concentrated photovoltaic (CPV) technologies are an effective tool for researchers to overcome the high running cost and the environmental impacts of conventional energy production systems. The principle of the CPV system is the use of low price concentrators that significantly reduces the cell area, and hence, allows for the use of high efficiency multi-junction solar cells of around 40% despite the high price of such solar cell [1]. However, the remaining incident energy is converted into heat, causing an increase in temperature in the solar cells [2]. The generated thermal energy in the CPV system might cause a significant decrease in its electrical efficiency and potentially damage the solar cell [3]. Therefore, using the efficient cooling technique in CPV systems will achieve a high electrical efficiency and enable the design of high concentration ratio (CR) systems. In addition, the extracted thermal energy can be used for domestic or industrial applications [4]. The method proposed in this study to cool the concentrated PV modules is the use of microchannel heat sink with nanofluids. Such a system preserves the high electrical efficiency while allowing excess heat to be used for assembling both the thermal and concentrated photovoltaic system in a hybrid CPV/thermal system so that the combined efficiency increases.

Many studies have been published on the cooling of photovoltaic systems relying on various methods. It was reported in the literature that the use of micro-channels or impinging jets attained the minimum thermal resistance among the cooling techniques utilized [5]. In addition, micro-channels can be incorporated into the back side of cells in the manufacturing process. It was noted that the microchannels achieve better temperature

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Nomenclature

C_p	specific heat of cooling fluid (J/kg K)
D_h	hydraulic diameter $D_h = 2H$ (m)
$G(t)$	incident solar radiation (W/m^2)
h	heat transfer coefficient (W/m^2 K)
H	microchannel height (m)
k	thermal conductivity (W/m K)
L	microchannel length, solar cell length (m)
$\dot{m}$	cooling fluid mass flow rate (kg/s)
Nu	Nusselt number $Nu = h \cdot D_h / K_{nf}$
P	pressure (Pa), thermal and electrical power (W)
q	rate of energy per unit area (W/m^2)
Re	Reynolds number $Re = \rho_{in} \cdot v_{in} \cdot D_h / \mu_{in}$
T	temperature (°C)
U_b	overall back heat transfer coefficient of insulation and ambient back convection loss (W/m^2 K)
U_t	overall heat transfer coefficient from the top surface of solar cell to ambient (W/m^2 K)
V	velocity vector (m/s)
V_w	wind velocity (m/s)

Greek symbols

α	absorptivity
β	backing factor and solar cell temperature coefficient (1/K)
ε	emissivity
τ	transmissivity
μ	fluid viscosity (Pa s)
σ	Stephan–Boltzmann constant $5.67 * 10^{-8}$ (W/(m^2 K^4))
ρ	fluid density (kg/m^3)
δ	thickness (m)
η	solar cell and thermal efficiency
φ	nanoparticle volume fraction

Subscripts

a	ambient
bs	back surface
c,g	from solar cell to glass
conv	convection
conv, $g-a$	convection loss from glass to ambient
eff	effective
el	electrical
g	glass
in	inlet
inc	incident
ins	insulation
l	base fluid or liquid
nf	nanofluid
out	outlet
p	particle
rad	radiation
ref	reference condition, $G = 1000$ W/m^2, $T = 25$ °C
sc	solar cell
sc, x	local solar cell
T	tedlar
th	thermal
w	wall
w	water
w, x	local wall

uniformity and high heat transfer rate from the solar cells [6]. Although many works relying on microchannel cooling method have been conducted on the performance of the integrated circuits and electronic devices, few studies have investigated this method with concentrated photovoltaic systems. Radwan et al. [7] used a microchannel heat sink in cooling a low concentration photovoltaic (LCPV) system. They indicated that using the microchannel cooling technique achieved a significant reduction in solar cell temperature. Further enhancement of the cooling process could be accomplished by increasing the fluid thermal conductivity through the use of nanofluids rather than pure fluids. The key principle of using nanofluids is that a significant enhancement in the heat transfer coefficient is acquired due to the increase of the mixture of thermal conductivity and the existence of a relative slip/drift velocity between the two phases that eventually enhances the flow mixing [8].

Karami and Rahimi [9] experimentally investigated the effect of nanofluids on PV cooling. They reported that the slurry of nanoparticles significantly decreased the average temperature of the PV cell compared to pure water. Furthermore, the performance of the cooling process was mainly dependent on the channel geometry and nanoparticle volume fraction. The nanofluids with particle volume fraction of 0.4% achieved the best performance, where the electrical efficiency reached 20.5% and 37.6% for the straight and helical microchannels, respectively. Xu and Kleinstreuer [1] developed a single phase model of a CPV cooling system relying on Al_2O_3–water nanofluid with the volume fraction of 5%. They indicated that nanofluids were preferable to using water, as nanofluids significantly improved the electrical and total efficiencies of the system. Further investigation was conducted by the same authors [10] to numerically study the thermal performance of the CPV system using Al_2O_3–water nanofluids. They concluded that the optimal PV operating efficiency of 20% was achieved for a cooling channel height of 10 mm, a nanoparticle concentration of 4%, and Re = 30,000 at a solar concentration ratio of 200.

Despite numerous studies on the use of nanofluids in cooling different applications, there are a limited number of publications related to the use of nanofluids in cooling CPVs. Therefore, the objective of this study is to investigate the performance of CPV cooling system of a wide microchannel heat sink with two types of nanoparticles, Aluminum Oxide (Al_2O_3), and Silicon Carbide (SiC), at different volume fractions. A comprehensive model is developed, which includes a thermal model for the photovoltaic layers, coupled with a two-phase thermo-fluid model for the microchannel heat sink. The effect of nanoparticles types, volume fraction, Reynolds number, and geometrical concentration ratio on the performance of the CPV/T system is investigated. The geometrical concentration ratio is identified by the ratio of the aperture area to the receiver area [11].

2. Theoretical analysis

In the present study, the performance of low concentrated photovoltaic cells with concentration ratio (CR) up to 40 is investigated. The CPV rests on a rectangular conductive wide microchannel with a height of 100 µm. Two different nanofluids containing Al_2O_3 and SiC nanoparticles with 20 nm diameters and volume fractions up to 4% are used as a cooling medium to avoid excessive cell temperatures and maintain a high cell efficiency. The flow Reynolds number is varied from 10 to 100. A constant sun radiation was assumed to be 1000 W/m^2. The incident solar radiation