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The influence of microchannel heat sink configurations on the performance of low concentrator photovoltaic systems

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HIGHLIGHTS

- A three-dimensional comprehensive modeling of the CPV/T system is developed.
- Parallel flow single layer heat sink attains the best performance of a CPV/T system.
- Counter flow single layer heat sink is the least effective cooling technique.

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ABSTRACT

A new cooling technique for concentrator photovoltaic (CPV) systems is developed using various configurations of microchannel heat sinks. Five distinct configurations integrated with a CPV system are investigated, including a wide rectangular microchannel, a single layer parallel- and counter- flow microchannel, and a double layer parallel- and counter- flow microchannel. A comprehensive, three-dimensional thermo-fluid model for photovoltaic layers, integrated with a microchannel heat sink, is developed. The model is numerically simulated and validated using the available experimental and numerical data. Based on the results, the temperature contours on a plane located at the mid-thickness of the silicon layer are presented at different operating conditions and heat sink configurations. Accordingly, the maximum local temperature can be detected and temperature uniformity can be accurately estimated. Furthermore, at a concentration ratio of 20, the CPV system integrated with a single layer parallel- flow microchannel heat sink configuration (B) achieves the highest cell net power, electrical efficiency, and the minimum cell temperature. On the contrary, at the same operating conditions, the use of a single layer counter-flow microchannel heat sink configuration (C) is found to be the least effective cooling technique. The results of this study can guide industrial designers to adopt compact heat sink configurations and simple designs in the manufacturing process of hybrid CPV-thermal systems.

1. Introduction

Concentrator photovoltaic (CPV) technologies have attracted much research attention in recent years because of its potential to address the high energy demands of the modern world, due, in part, to rapid population growth and the depletion of fossil fuels. However, the issue of cooling these systems for effective functioning still remains a significant roadblock to their wide-spread use. As sunlight concentration on photovoltaic cells causes a significant increase in the cell temperature, the cells' system efficiency considerably decreases, while high operating temperatures lead to irreversible decay of the solar cells in the long term. Therefore, the use of efficient cooling techniques for concentrator photovoltaic systems will allow for a higher level of electrical efficiency, and will mitigate any potential damage to the cell [1,2].

Many numerical and experimental investigations have been carried out over the past several years to address the issue of cooling photovoltaic cells. It was reported that an appropriate and effective cooling technique must attain a higher cell efficiency, a better cell temperature uniformity, and consume lower levels of pumping power [3]. Thus, this study examines various cooling methods for CPV systems, including passive cooling, active cooling using forced convection [4,5], two phase convective cooling [2], and jet impingement cooling [6,7]. Most recent research only considers a one-dimensional analysis of the thermal model where only the temperature variation with thickness is tested. Tiwari and Sodha [8] developed a one-dimensional thermal model of the photovoltaic thermal (PV/T) system. Based on their model, an

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Nomenclature

A	solar cell area [m^2]
C	specific heat of coolant [J/kg K]
D_h	hydraulic diameter [m]
G(t)	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 component in y-direction [m/s]
V_w	wind velocity [m/s]
w	velocity component in z-direction [m/s]
W	channel width, thickness of fin between flow channel and neighboring flow channel and width of the solar cell [m]

Greek symbols

α	absorptivity
β	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]
λ	molecular mean free path [m]
η	solar cell and thermal efficiency

Subscripts

a	ambient
b	back sheet or tedlar
ch	channel
conv, g-a	convection loss from glass to ambient
el	electrical
f	fluid and fin spacing between the flow channel and the neighboring flow channel
Fric.	friction
g	glass
in	inlet
int	interval part of EVA
net	net
rad, g-s	radiation loss from glass to sky temperature
ref	reference condition, G = 1000 W/m^2, T = 25 °C
s	sky
Sc	silicon wafer
th	thermal
w	wall

analytical expression for the cell temperature, water outlet temperature, and thermal efficiency as a function of metrological conditions was derived. In their work, both air and water were used as coolant fluids for their suggested designs. They found that using water achieves a higher daily efficiency compared to air, for all studied designs except the design of glazed PV without tedlar. Their work was extended to include the electrical model of the PV module as reported by Sarhaddi et al. [9]. They concluded that the results obtained from the combined thermal and electrical models were more precise than those obtained from the thermal model only. Several researchers [10–13] applied the same model to predict PV/T system performance.

A further step toward a more accurate thermal model for the PV/T system was the development of the two-dimensional analysis. Xu and Kleinstreuer [14] developed a two-dimensional thermal model for concentrator photovoltaic thermal (CPV/T) systems for both a generic crystalline silicon and multi-junction solar cells. In their model, they used Al_2O_3-water nanofluid as a coolant with channel heights ranging from 2 mm to 14 mm. They proposed to solve the Navier Stokes equations along with the fluid energy equation to predict the exact behavior of the thermal absorber rather than using an empirical correlation. Rejeb et al. [15] developed a two-dimensional model for the PV/T system. They reported that the increase in the heat conduction coefficient between the back side of the photovoltaic module and the absorber plate enhances the electrical and thermal efficiency of the PV/T systems.

Recently, a two-dimensional model for concentrator photovoltaic systems with a microchannel heat sink was developed by Radwan et al. [16,17]. In their study, a comparison between the conventional cooling technique and the microchannel heat sink technique was conducted using CPV systems operating up to concentration ratio (CR) of 40. They concluded that using a microchannel cooling technique attained the ultimate possible reduction of solar cell temperature due to the high heat transfer coefficient associated with micro-scale thermal absorbers. The study concluded that the two-dimensional thermal model correctly predicts the thermal behavior of conventional thermal absorbers while the change in the third dimension could be insignificant. However, in non-traditional configurations where the temperature variation in the third dimension is a major, the two-dimensional modeling fails to predict the precise behavior of the PV/T systems.

To overcome the limitations associated with one and two-dimensional models of the PV/T systems, a few researchers were developing a three-dimensional model. Siddiqui and Arif [18] developed a three-dimensional hybrid structural, electrical and thermal model of the PV/T system under normal solar radiation and varying climatic conditions. They recommended three-dimensional modeling as an efficient tool to select the most effective heat exchanger in designing the PV/T systems. Subsequently, Zhou et al. [19] developed a three-dimensional thermal model for the uncooled, generic polycrystalline cell using finite element analysis. In their study, the three-dimensional temperature distribution of the cell was simulated under the effects of different metrological conditions. They reported that three-dimensional models are needed to capture temperature uniformity and temperature distribution especially in PV/T systems with complex thermal absorber structure. In addition, three-dimensional models are more flexible and can easily be adopted 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 [20]. One of the most essential parameters is the solar cell temperature uniformity. It was found that the cell efficiency declines due to the cell non-uniform temperature distribution that causes a reverse saturation current [21]. 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. Therefore, a three-dimensional model greatly assists in predicting the temperature distribution of a solar cell, and consequently, allows the temperature uniformity of a solar cell to be accurately estimated.

The originality of the present work is based on two main concepts: first, a new comprehensive three-dimensional thermo-fluid model for photovoltaic layers, integrated with irregular configurations of microchannel heat sinks is developed. This model will predict the temperature contour of the solar cell layer and accordingly predict the existence of potential hotspots. Second, a novel microchannel heat sink with