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Analysis and simulation of concentrating photovoltaic systems with a microchannel heat sink

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ABSTRACT

A new cooling technique for low concentration photovoltaic (LCPV) system is presented using a microchannel heat sink. This study investigates the influence of operating conditions such as concentration ratio, cooling mass flow rate, wind speed, ambient temperature, and cooling liquid inlet temperature on the performance of the low concentration photovoltaic thermal system. A comprehensive thermal model is developed which includes a thermal model for the photovoltaic, coupled with a thermo-fluid model for the microchannel heat sink. The numerical results are validated using different sets of the available experimental and computational data. The variation of solar cell temperature and electrical and thermal efficiency with operating conditions is investigated using the energy budget approach to interpreting the influence of operating conditions. The predicted results indicate that the use of a microchannel heat sink is a very effective cooling technique. This is especially true for concentrated photovoltaic systems in which a significant reduction in solar cell temperature is attained, along with uniform temperature distribution. At a microchannel flow Reynolds number of 100, it is found that at a concentration ratio of 20, the local solar cell temperature varies between 33.5 and 35.6 °C, while at a concentration ratio of 40 the local solar cell temperature ranges from 37 and 41 °C. Furthermore, at a concentration ratio of 40, the electrical efficiency reaches 18.5%, and the thermal efficiency achieves the maximum of 62.5%, whereas the power loss in microchannel friction is estimated to be about 0.4% of the electrical power output. Finally, a comparison between the previous solar cell temperatures using different cooling systems and the current results using microchannel is conducted using the dimensional analysis approach to finding the common groups for the various cooling methodologies used. Comparisons indicate that using a microchannel cooling technique achieves the utmost possible reduction of solar cell temperature.

1. Introduction

The Photovoltaic thermal system can be considered the most promising source of clean renewable energy, as it converts solar radiation into electricity and heat. A small fraction of absorbed sunlight is converted directly into electricity in Photovoltaic (PV) cells. The electrical efficiency is approximately 20% for silicon solar cells and 40% for multi-junction solar cells (Xu and Kleinstreuer, 2014a,b). The remaining absorbed solar radiation is converted into heat, which eventually causes the temperature to rise in PV cells. It is found that the PV output power is directly proportional to the absorbed solar radiation (Duffie and Beckman, 2013) and the PV cell efficiency declines with increasing the cell temperature (Rahimi et al., 2013). In addition, the higher the PV temperature, the lower the electrical efficiency, and the greater the possible damage to the cell (Gao et al., 2010). To improve the electrical efficiency and avoid a potential damage, a concentrating PV system associated with an effective cooling technique is of crucial importance. Efficient use of such systems can be attained not only by using the output electrical energy but by utilizing the dissipated heat as a source of thermal energy as well. Consequently, the suggested method to cool the concentrated PV modules is to use the hybrid systems to recover part of the waste heat and use it for other practical applications. This system maintains high electrical efficiency, and excess heat could be used for assembling both the thermal and photovoltaic system in a hybrid PV/thermal system so that the combined efficiency increases (Royne et al., 2005).

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Nomenclature

b	solar cell width (m)
C_f	specific heat of cooling fluid (J/kg K)
CPV/T	concentrated photovoltaic thermal
D_h	hydraulic diameter $D_h = 2H$ (m)
E	rate of energy (J/s)
$G(t)$	concentrated solar flux on the solar cell surface (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)
$\dot{m}$	mass flow rate of cooling fluid (kg/s)
Nu	Nusselt number
P	pressure (Pa)
PV	photovoltaic
PV/T	photovoltaic thermal
q	rate of heat per unit area (W/m^2)
Re	Reynolds number
T	temperature (K)
u	x-velocity component (m/s)
U_b	overall back heat transfer coefficient from the lower wall of the microchannel to atmosphere (W/m^2 K)
U_f	overall heat transfer coefficient from back of solar cell to the flowing fluid (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 $\vec{V} = u\vec{i} + v\vec{j}$.
v	y-velocity component (m/s)
V_w	wind velocity (m/s)

Greek symbols

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

Subscripts

a	ambient
ab	absorbed
c, g	from solar cell to glass
$conv., g–a$	convection loss from glass to ambient
el	electrical
f	fluid
g	glass
in	inlet
ins	insulation
out	outlet
$rad.$	radiation
$rad., g–s$	radiation loss from glass to sky temperature
ref	reference conditions, $G = 1000$ w/m^2, $T = 25$ °C
s	sky
sc	solar cell
sc, x	local solar cell
t	top surface
T	tedlar
th	thermal
w	water
w, x	local wall
$wall$	wall

A great number of researchers investigated the cooling of photovoltaic systems using various methods. Some of these researchers focused on cooling the PV or CPV system from the back side, using different mini scale thermal absorbers (Zhao et al., 2011; Ramos-Alvarado et al., 2011; Yang and Zuo, 2015) and large-scale absorbers (Rejeb et al., 2015; Singh et al., 2016; Bahaidarah et al., 2014). Other research was conducted using one side surface film cooling (Moharram et al., 2013), both sides surface film cooling (Zhao et al., 2011), and the immersion of the solar cell into water (Tina et al., 2012). It was reported that using micro-channels or impinging jets attained the minimum thermal resistance among the used cooling techniques (Rosell et al., 2011). In addition, micro-channels can be incorporated into the back side of cells in the manufacturing process. While many studies using the 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. The microchannel heat sink (MCHS) is a new concept compatible with many electronic applications because of its ability to remove a large amount of heat from a small area. The main idea is that the heat transfer coefficient scales inversely with the flow characteristic dimension. Consequently, a significant reduction in the thermal resistance can be achieved with the use of microchannel cooling system. In addition, the solar photovoltaic layers are manufactured in a micro-sized. So the integration of microchannel heat sink achieves a compact design of CPV/T system rather than the conventional cooling techniques using a large scale cooling.

Rahimi et al. (2013) experimentally studied the performance of the combination of micro-channels and a photovoltaic module as a hybrid PV/T system using water as a coolant. In their experiments, the microchannel hydraulic diameter was 0.667 mm, and the Reynolds number (Re) varied up to 70. They reported that the power was increased by approximately 30% compared to uncooled conditions. Reddy et al. (2014) concluded, based on numerical simulation, that the optimum dimensions of the microchannel were 0.5 mm width and aspect ratio of 8. Moreover, the pressure drop was found to be low in straight flow channels. Ramos-Alvarado et al. (2011) numerically calculated the pressure loss and temperature uniformity of the heated walls of different proposed microchannel configurations. They suggested a new design, achieving a smaller pressure drop and better flow and temperature uniformity. They recommended using microchannel distributers for cooling the concentrated PV cells, fuel cells, and electronics. Agrawal and Tiwari (2011a,b) developed a one-dimensional thermal model and validated it experimentally at different heights ranged from 0.5 to 5.0 mm for single and multichannel design. They concluded that the electrical and thermal efficiency of the multichannel PV/T system were higher than those of the single channel PV/T system.

The above survey of the literature indicates that most of the used cooling channel heights are greater than 300 μm for all previously studied PV/T systems. As reported (Kandlikar, 2014), the flow passages of a typical micro heat exchanger were classified by ($10\ \mu\text{m} < H \leqslant 200\ \mu\text{m}$) as micro-channels, ($200\ \mu\text{m} < H \leqslant 3$ mm) as mini-channels and ($3\ \text{mm} < H$) as conventional channels