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Enhancement of the cooling capability of a high concentration photovoltaic system using microchannels with forward triangular ribs on sidewalls

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HIGHLIGHTS

- A microchannel heat sink device (MCHSD) maintains the solar cell temperature < 301 K.
- The hydraulic and thermal performance of an MCHSD with ribs were determined.
- The direct integration “Solar cell-MCHSD” enhances the thermal performance.
- Passive cooling systems are not recommended for HCPV.

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ABSTRACT

Numerical simulations were performed to investigate a microchannel heat sink device as cooling option for a high concentration photovoltaic system. COMSOL Multiphysics 5.1 software is used to solve three-dimensional equations which consider conjugate heat transfer, viscous dissipations, and temperature-dependent-properties. This study investigates the integration of microchannels with complex geometric features on its inner walls into the solar cell structure, to enhance the heat transfer performance of a microchannel heat sink-based active cooling system. Inner sidewall mounted forward triangular ribs are considered in aligned and offset distributions along the microchannel walls. In addition, numerical analysis is developed for a conventional flat plate heat sink integrated to a high concentration photovoltaic system to stablish a baseline solar cell temperature. The numerical results show that a micro-channel heat sink device can control and keep in very low range the solar cell temperature (< 301 K). Compared to a smooth microchannel, forward triangular ribs installed on the sidewalls enhance the heat transfer capability. Microchannels with aligned and offset rib distributions increase the Nusselt number between 1.8 and 1.6 times, respectively, and increase the average friction factors between 3.9 and 2.3 times, respectively. The microchannel heat sink device with forward triangular ribs is more efficient and effective at $Re \leq 200$, since the pumping power reaches a high percentage of the total power generated by solar cell when $Re > 200$. At $Re = 400$, the pumping power reaches 41% and 23% of the total power generated by a multi-junction solar cell in the aligned and offset rib distribution, respectively. The pumping power is greatly reduced while using smooth microchannel, because the maximum pumping power is only 9.5% of the solar cell power at $Re = 400$, however, the resulting solar cell temperature is slightly higher compared to microchannels with aligned and offset rib configurations. A microchannel heat sink provides a more effective cooling solution compared to a passive flat plate heat sink for a high concentration photovoltaic system. In addition, the possibility of direct integration of a microchannel heat sink into a solar cell structure as proposed in this study, represents an interesting option to feasibly increase thermal performance to a considerable level by maintaining the solar cell temperature in a very low range.

1. Introduction

A new generation of photovoltaic (PV) technology known as multi-junction solar cells, which are multiple p–n junctions made of different

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semiconductor materials, is currently available. Multi-junction solar cells are used in high concentrator photovoltaic system (HCPV), where lenses and mirrors are used to concentrate the sunlight to reduce the use of semiconductor materials and the area required to generate output power [1]. As only a fraction of the solar radiation can be converted into electrical power, the action of concentrating and increasing the amount of solar energy onto a multi-junction solar cell produces an overheating of the solar cell and adversely affects the conversion efficiency and solar cell durability. Kinsey [2] noted that triple-junction solar cells are particularly sensitive to temperature increases, and the conversion efficiency of a three-junction solar cell can decreases 0.05% for every °C increase of the cell temperature. The overheating implies a reduction of conversion efficiency and increases the heat generated by the solar cell, leading to higher overheating. In addition, a high cell temperature accelerates the degradation of the solar cell, affects deformation on the cell surface, produces delamination of the encapsulant layer, and develops of microcracks on the cell because of the different thermal expansion coefficients of the different materials composing the cell structure [3]. Royne et al. [4] concluded that temperature is always the limiting factor for concentration solar cells and mesoscale cooling devices may not be able to remove great amount of heat from small surfaces and micro-technology can assure faster performance

Different techniques have been studied and evaluated to handle the overheating of multi-junction solar cell subjected to high solar concentration. Passive cooling techniques has been able to handle the overheating because of the large surface available for heat transfer and because they do not require electrical or mechanical energy input to operate [4]. Active cooling systems are more effective at high concentration levels, and different innovated active cooling techniques have been proposed, for example, Han et al. [5] studied electrical and thermal performance of silicon CPV immersed in dielectric liquids. However, Royne et al. [4], Radwan et al. [6], and [7] highlight microchannel heat sinks as a great option to refrigerate multi-junction solar cells subjected to high solar concentration because of their high thermal performance in small areas and the possibility of being incorporated in the solar cell manufacturing process. In addition, a cooling system integrated to an HCPV should be designed considering technical and economic aspects [3], such as: (1) cost of the heat sink materials; (2) concentrator factor; (3) weight added to the tracker by the cooling system; and (4) miniaturization of the solar cell. The heat generated by a multi-junction solar cell can be employed to increase the efficiency of the entire system, by having an effective and efficient active cooling system. Although hybrid systems are not in the scope of this article, it is worthy to highlight that different investigators have analyzed CPV-based hybrid systems. For example, Xue et al. [8] developed a parametric analysis of a hybrid CPV-CSP system considering an organic-Rankine cycle and found that the hybrid system increased its efficiency by about 20% compared with the CPV-alone system. Rezania and Rosendahl [9] analyzed a hybrid concentrated photovoltaic-thermoelectric system (CPV-TEG) and investigated the feasibility of different types of heat sinks. Their results indicated that the thermoelectric contribution power generation was enhanced at high concentration levels, and optimal values for heat transfer coefficient in the heat sink offered minimum energy cost.

From the work of Tuckerman and Pease [10], a microchannel heat sink provided a solution in micro-scale applications because of its ability to remove a large amount of heat from a small area. Microchannels have been investigated as refrigeration cooling device for electronic applications because of the continuous miniaturization of electronic components. However, few studies have investigated the use of microchannel heat sink in HCPV systems. Recently, Radwan et al. [6] evaluated the influence of a microchannel heat sink configuration on the performance of low concentrator photovoltaic system. They concluded that microchannels are an effective method for concentration ratios up to 20 and that a parallel flow microchannel heat sink achieves the highest cell net power. Radwan and Ahmed [7] developed, analyzed and simulated a two-dimensional model of a low concentrating photovoltaic system with smooth 100 μm high microchannel heat sink. The study evaluated the influence of operating conditions such as concentration ratio, cooling mass flow rate, wind speed, and ambient temperature. They found that the microchannel generated a significant reduction in cell temperature with a uniform temperature distribution, and when Re = 100 and CF = 20, the solar cell temperature varied between 306 and 309 K. Other investigations of a microchannel heat sink employed in a CPV system were performed by Rahimi et al. [11]. They studied the performance of a microchannel and photovoltaic module as a hybrid PV/T system using water as coolant. They reported that the conversion efficiency increased by approximately 30% compared to that of uncooled conditions. Reddy et al. [12] developed a numerical investigation of a microchannel heat sink for solar CPV system by evaluating different microchannel widths and aspect ratios. They concluded that the optimum width of a microchannel was 500 μm an aspect ratio of 8. Moreover, the pressure drop was found to be low in straight flow channels. Ramos-Alvarado et al. [13] 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 concentrated PV cells, fuel cells, and electronics. Agrawal and Tiwari [14] developed a one-dimension thermal model and concluding that the electrical and thermal efficiency of the multichannel PV/T system were higher than those of a single channel PV/T system. Kermani et al. [15] fabricated and investigated a manifold microchannel heat sink for a cooling concentrator photovoltaic system with CF = 1000 suns. The heat sink distributed the coolant through alternate inlet and outlet channels in a direction normal to the surface, thus resulting in a greater heat transfer dissipation rate because of the lower pressure drop across the surface to be cooled. W. Chong et al. [16] analyzed the performance of a water-cooled multiple-channel heat sinks for ultra-high concentrator photovoltaic system. With a concentration level of 1800 suns, they achieved a conversion efficiency of 31.8% for their microchannel heat sink designed.

With respect to the performance of microchannel heat sinks, a large number of investigations have been performed. The tiny channel size introduces high convection coefficients even for laminar flow regimen, which is the predominant regimen. The rectangular smooth microchannel was the basic geometric configuration evaluated by the work [11] and was validated with analytic expression, however, in the smooth microchannel (SMC), hotter fluid accumulates at the channel wall and cooler fluid along the channel core because of the continuous growth of the thermal boundary layer. Therefore, earlier studies sought to enhance the thermal performance of a smooth rectangular microchannel by evaluating different aspect ratios, channel lengths, and wall thicknesses. Some researchers introduced disruption of the boundary layer, and others evaluated changes in the cross-section shape of a microchannel [17].

Disruption of the boundary layer was analyzed by incorporating cavities, porous medium, ribs and groove structures where the heat transfer performance is enhanced because the disruption elements tend to blend hotter and cooler fluids. Ribs have been analyzed in different shapes and configurations inside channels. Chai et al. [18] performed a parametric investigation based on numerical simulations with the use of fan-shaped ribs with aligned and offset arrangements installed on the inner parallel sidewalls. They reported that for the studied Reynolds number range, the ribbed configuration increased the average Nusselt number of the aligned configuration by 6–101% and 4–103% for the offset arrangement. Wong and Lee [19] developed a numerical simulations of microchannel heat sink with triangular ribs in transverse microchambers. They found that heat transfer rate increased with an increment of rib-width and height, but decreased with an increase in rib length. Chai et al. [20] extended the work developed by [19]. They numerically analyzed different rib shapes in transverse microchambers, with rectangular, backward triangular, diamond, forward triangular and ellipsoidal shapes. They reported that the ribs in microchambers effectively prevent the decline of the local heat transfer coefficient and the ellipsoidal ribs in the microchambers showed the best heat transfer performance. Chai et al. [21] analyzed through numerical simulations