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# Performance evaluation of new modified low-concentrator polycrystalline silicon photovoltaic/thermal systems

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ABSTRACT

A modified polycrystalline silicon solar cell structure is introduced to enhance the heat dissipation process from the cell's silicon layer. The modification involves two steps. First, the Ethylene-Vinyl Acetate (EVA) layer underneath the silicon wafer of a conventional solar cell is replaced with a nanocomposite layer that includes an EVA matrix doped with Boron Nitride (BN) nanoparticles at different loading ratios of 20, 40, and 60%. Second, the Tedlar Polyester Tedlar (TPT) layer is substituted with a high thermal conductivity aluminum backing foil layer. To assess the enhancements to the modified solar cell in comparison to the conventional cell, a three-dimensional thermo-fluid model is developed. The model is numerically simulated and the results are validated with the available experimental, numerical, and analytical results. The findings reveal that at a concentration ratio up to 3.5 where no external cooling technique is used, the modified cell attains a slight reduction in solar cell temperature compared to the conventional cell. On the other hand, at a concentration ratio of 20, where the solar cell is integrated with a microchannel heat sink, a significant reduction of cell temperature is observed compared to the conventional cell. It is found that at a concentration ratio of 20, and a coolant mass rate of 100 g/min, the maximum temperature of the modified cell with 60% BN and an aluminum back sheet is 66 °C, while the conventional solar cell temperature is 108 °C. Additionally, of the two cells, the modified solar cell produces the highest net power of 45 W, and achieves the highest electrical and thermal efficiency of 17.5%, and 70.8%, respectively. Meanwhile, the conventional solar cell produces 34 W, and attains an electrical and thermal efficiency of 13.5%, and 69%, respectively. These findings can guide designers in the industrial field to adopt this type of modified solar cell to improve the performance of low concentrator photovoltaic systems.

## 1. Introduction

The generic polycrystalline silicon solar cell is currently the most popular commercial solar panel that converts solar energy directly into electricity. In this type of solar cell, the silicon wafer is encapsulated in a high transparency elastomeric Ethylene Vinyl Acetate (EVA) copolymer. The EVA possesses some remarkable properties such as low absorption of moisture, strong adhesion to glass cover, and low resin cost [1]. Thus, the purpose of the EVA is to inhibit degradation and corrosion of the device induced by the penetration of oxygen and moisture into the silicon wafer. Moreover, high optical transmissivity along with high electrical resistivity makes EVA is an outstanding encapsulating material. However, improving the thermal conductivity of the upper layer will have approximately no effect on heat dissipation from the cell. Furthermore, the EVA is a polymeric material that has a much lower thermal conductivity than ceramic or metal materials. This causes the EVA layer to act as a bottleneck for heat removal from the back side of the silicon wafer to the thermal absorber in the concentrator photovoltaic thermal (CPV/T) system [2]. Accordingly, the absorbed excess energies cause a substantial increase in the cell temperature which unfavorably decreases the electrical conversion efficiency. This is especially true in the case of using concentrator photovoltaic system (CPV).

The basic principle of CPV systems is relied on the utilization of cost-efficient concentrating optics such as Fresnel lenses and mirrors. Accordingly, the cell area could be significantly reduced, and therefore, allows for the use of high-efficiency cells that decrease the cost of electricity compared with standard flat-plate PV technology [3]. In the low-concentrator photovoltaic systems, crystalline silicon (c-Si) solar cells are normally used with low solar concentration ratios (CR) below 100 [3]. It was reported that the polycrystalline silicon solar cell efficiency decreases by about 0.5% per one degree of raised temperature in the silicon layer beyond the nominal operating temperature [4]. Therefore, avoiding the high cell temperature is essential in order to

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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(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) |
| R | reflectivity in the optical properties |
| *Re* | Reynolds number |
| T | temperature (°C) |
| u | velocity component in x-direction (m/s) |
| v | velocity component in y-direction (m/s) |
| V | wind velocity (m/s) |
| w | velocity component in z-direction (m/s) |
| W | width of the channel and width of the solar cell (m) |

*Greek symbols*

| | |
|---|---|
| α | absorptivity |
| β | solar cell backing factor and temperature coefficient (1/K) |
| ε | emissivity |
| τ | transmissivity |
| μ | fluid viscosity (Pa·s) |
| σ | Stephan-Boltzmann constant $5.67*10^{-8}$ ($W/(m^2 \cdot K^4)$) |
| ρ | fluid density ($kg/m^3$) |
| δ | thickness (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 |
| 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, $G_{ref} = 1000\ W/m^2$, T = 25 °C |
| s | sky |
| sc | solar cell |
| th | thermal |
| w | wall and wind |

enhance the solar cell's efficiency and other major performance parameters of the CPV system.

To enhance the performance of CPV systems, research has been developing in two main directions. The first direction focuses on developing efficient cooling techniques, while the second direction focuses on enhancement of the thermal conductivity of the EVA copolymer materials. Substantial attention has been given over the past several years to the first direction, the issue of cooling techniques for photovoltaic cells, and many numerical and experimental investigations have been carried out. It was reported that the appropriate cooling technique must accomplish a higher cell efficiency, a better cell temperature uniformity, and a minimum consumed pumping power [5]. Thus, various cooling methods for CPV systems have been employed including passive cooling, active cooling using forced convection, two-phase convective cooling, and impingement cooling [6–8].

Some researchers focused on cooling the CPV system from the back side, using different mini scale thermal absorbers [9–11], and large scale absorbers [12,13] or both sides surface film cooling [9]. It was reported that using micro-channels or impinging jets attained the minimum thermal resistance among the cooling techniques tested [14]. In addition, micro-channels can be incorporated into the back side of cells during the manufacturing process. Accordingly, Radwan et al. [15] developed a cooling technique for the CPV system using a microchannel heat sink. They performed a comparison between solar cell temperatures using different established cooling systems and their microchannel heat sink. Comparisons indicated that using a microchannel cooling technique achieves the utmost possible reduction of solar cell temperature. Further research of microchannel cooling heat sink configurations was performed by Radwan et al. [16]. In their work, five different configurations were tested, including parallel micro-channel flow, counter micro-channel flow, single and double layer microchannels, and a single layer flat micro-channel integrated with a CPV system. They concluded that a CPV system integrated with a parallel flow single layer microchannel heat sink configuration attains the highest cell net power, and a minimum cell temperature. Furthermore, Yang and Zuo [17], experimentally investigated a novel multi-layer manifold microchannel heat sink to effectively reduce the solar cell temperature and improve the cell temperature uniformity operating under solar concentrations up to 89 suns. They concluded that the proposed configuration has a high heat transfer coefficient with a slight pressure drop lower and they recommended that the examined hybrid CPV-thermal (CPV/T) system has a satisfactory net output power.

In the second research direction, the thermal conductivity of EVA is very low at about 0.311 W/(m·K). In addition, the back sheet tedlar layer has a low thermal conductivity of 0.15 W/(m·K). These two low thermal conductivity layers are the bottlenecks for heat dissipation from the solar cell. Therefore, much research has been conducted to enhance the thermal conductivity of EVA copolymer materials without sacrificing their main function with the higher optical transparency. An interesting review regarding the recent advances in controlling the microstructure of polymer composites to achieve high thermal conductivity was published by Chen et al. [18]. This review summarizes the fundamental design principles of highly thermally conductive composites and the key factors affecting thermal conductivity. In addition, the characteristics of several thermally conductive fillers such as metal particles, carbon nanotubes, and ceramic particles, for instance aluminum oxide or boron nitride, were reported. The dependence of the thermal conductivity of composites on the percentage of filler, and the overall composite structure was discussed. However, a few related experiments regarding the application of the EVA to solar cells were conducted by several researchers. Lee et al. [19] experimentally investigated the augmentation of the thermal conductivity of the rear EVA layer. Their results indicate that the EVA composite encapsulating rear films filled with thermally conductive nanoparticles (fillers) such as Zinc Oxide (ZnO) or Boron Nitride (BN) significantly enhances the PV efficiency. Allan et al. [20] reported that doping EVA with BN significantly increases the thermal conductivity from 0.24 up to 0.8 W/m·K for the sample of 60% BN filler. They investigated the effect of doped EVA on the solar cell temperature. Their results indicated that a reduction of PV temperature of about 6 % was achieved at lower irradiance. Allan et al. recommended that a significant reduction of cell temperature and accordingly higher performance of PV could be expected at a higher concentration of irradiance. Lee and Dai [21] studied the influence of modifying ZnO filler with surface-treating agents on the

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