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THERMAL MODELLING OF MULTI-JUNCTION SOLAR CELLS ASSEMBLY UNDER FRESNEL-BASED CONCENTRATOR PHOTOVOLTAIC/THERMAL SYSTEM

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ABSTRACT

High solar irradiance concentration on multi-junction (MJ) solar cells leads to extremely high cell temperature, which significantly reduces cell efficiency and can lead to cell damage. Therefore, heat dissipation via cooling techniques is essential for photovoltaic solar cells under high concentration. This work develops a 3D thermal model for an assembly of four MJ solar cells with a Fresnel-based HCPV/T system and investigates the capability of active cooling to maintain a maximum solar cell surface temperature under the operating limit (i.e. 80°C). Solar cells temperatures are predicted for different concentration ratios (CRs) and inlet water velocities, varying between 200X–1000X and 0.01–0.4 m/s, respectively. At a CR of 1000X and a water velocity of 0.3 m/s, a maximum cell temperature of 79.2°C can be achieved, which is below the maximum operating temperature. Furthermore, the outlet water average temperature for multiple concentrator photovoltaic (CPV) assemblies were performed. The results showed that the solar cells' temperatures decreased with increased inlet water velocity, and sufficient temperature uniformity was achieved by active water cooling. In addition, the outlet water's average temperature increased considerably with the number of CPV assemblies. It was found that with four CPV assemblies using a moderate inlet water velocity of 0.01 m/s, the average outlet water temperature rose from input temperature i.e. 25°C to 44°C and 62°C for a CR of 300X and 600X, respectively.

Keywords: Concentrating photovoltaic, concentration ratio, multi-junction solar cells, active cooling, thermal modelling, Fresnel lens.

1. INTRODUCTION

With climate change and global warming, the focus has shifted towards solar energy as a low-cost and sustainable alternative energy source. High concentrator photovoltaic (HCPV) technology based on high-efficiency multi-junction (MJ) solar cells has been listed as one of the most promising and cost effective renewable energy sources [1]. In these systems, the primary strategy is to reduce the area of solar cells and increase the intensity of solar radiation on the cells using low-cost optical components [2]. The HCPV system takes advantage of using MJ cells because of their high efficiency and excellent performance under concentrated illumination [3]. Recently, MJ cells recent have been reported to achieve up to 46% conversion efficiency [4]. Almost half the sunlight absorbed in these cells is converted directly into electricity, while the rest is converted into heat, which leads to increased cell temperatures. HCPV performance relies on the temperature of the solar cell and that temperature's uniformity. The cooling unit design is an important consideration, as solar cells can suffer efficiency loss (0.45% per °C) or incur irreversible damage due to excessive temperatures [5, 6].

The thermal management of the concentrator photovoltaic (CPV) system has recently been studied extensively [7], though most of this research considers thermal numerical models for a HCPV that used a single concentrator solar cells. Limited literature is available on HCPV systems using a single set of concentrators that integrate with multiple MJ solar cells, other than Burhan et al. [8], who designed and tested the optical and electrical performance of four MJ solar cells using multi-leg homogenizer CPV assembly but with no thermal analysis or testing. The present work develops a new optical concentration system that uses Fresnel and plano-concave lenses to deliver parallel rays to the multi-leg homogenizer, which distributes the solar rays uniformly to the MJ solar cells. Additionally, the thermal modelling of four MJ solar cells assemblies under this high concentration optical system with active water cooling is examined to predict the cells and outlet water temperatures under various concentration ratios (CRs) and inlet water velocities.

2. METHODOLOGY

Optical ray tracing technique and thermal modelling of high CR MJ solar cells using different CR of 200X, 400X, 600X, 800X and 1000X have been modelled using COMSOL Multiphysics 5.3a software. A 3D comprehensive optical/thermal is developed. The model solves the conjugate heat transfer governing equations of the water cooling channel designs integrated with the MJ cell. A schematic diagram of the HCPV/thermal (HCPV/T) system geometry shown in Fig. 1 was drawn using SolidWorks software and then imported into COMSOL software. The system consists of a Fresnel lens as the primary optical element, a plano-concave lens and multi-leg homogenizer as the secondary optical elements and four MJ solar cells. The Fresnel lens concentrates the direct sunlight onto the plano-concave lens, and a combination of Fresnel and plano-concave lenses provides collimated light (i.e. area concentration is achieved instead of point focus concentration). Then, the homogenizer is placed to divide the received solar radiation into four parts and to further guide, distribute and concentrate them over the surface of four MJCs placed at the homogenizer's four outlets. In this study, the AZURSPACE III-V triple junction solar cell was made of GaInP / GaInAs / Ge layers with an active area of 10 × 10mm^2.

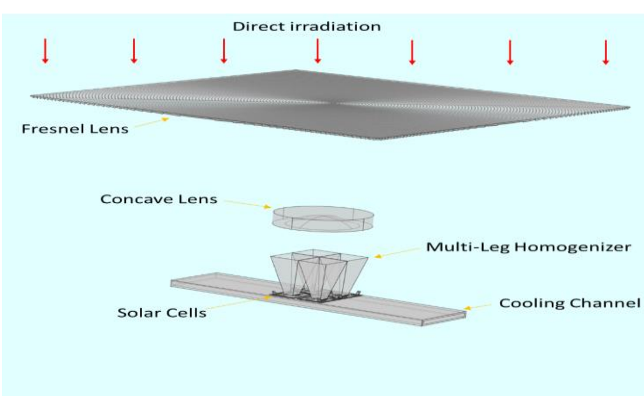

Fig. 1. Schematic of the investigated Fresnel-based HCPV/T system

The amount of input energy converted to heat (q_{heat}) can be obtained using the following equation [9]:

$$q_{heat} = q_{rad} \cdot (1 - \eta_{cell}) . CR, \quad (1)$$

where q_{rad} is the solar radiation incident on the solar cell surface, η_{cell} is the electrical efficiency and CR is the concentration ratio.

The electrical efficiency of the solar cell as a function of cell operating temperature can be calculated with the following equation [10]:

$$\eta_{cell} = \eta_{Ref} - [\beta_{Thermal} \, (T_{cell} - T_{Ref}), \quad (2)$$

where η_{Ref} is cell electrical efficiency at CR, $\beta_{Thermal}$ is the thermal temperature coefficient, T_{cell} is the solar cell's average temperature and T_{Ref} is the reference temperature of 25°C. The heat dissipated by conduction between the solid layers of the solar cell assembly and at the top surface of the cooling channel is determined by Fourier's law [11]:

$$q_{cond} = -K\boldsymbol{\nabla T}, \quad (3)$$

where q_{cond} is the conduction heat transfer rate and K is the thermal conductivity of each solid material.

Heat loss caused by convection at the top and bottom surfaces of solar cell assembly is described as follows [11]:

$$q_{conv} = h.\,A.\,\boldsymbol{\Delta T}, \quad (4)$$

where q_{conv} is the convection heat transfer rate, h is the convective heat transfer coefficient and A is the convection surface area.

Heat that is lost to the ambient due to thermal radiation is calculated by the following equation [11]:

$$q_{rad} = \varepsilon \,.\, \sigma \,.\, A \,.\, ({T^4}_{surf} - {T^4}_{amb}) \quad (5)$$

where q_{rad} is the radiation heat transfer rate, ε is the emissivity of the material, σ is the Stefan–Boltzmann constant, T_{surf} is the surface temperature and T_{amb} is the ambient temperature.

The following assumptions have been considered [11, 12]:

- The direct solar irradiance is 1000W/m^2 and is distributed uniformly on the solar cell surface.

- The applied concentrations to be examined are 200X, 400X, 600X, 800X and 1000X.
- The inlet cooling water temperature is uniform and assumed to be 25°C.
- The inlet water velocity inside the cooling channel ranges 0.01–0.15 m/s (laminar flow case) and 0.2–0.4 m/s (turbulent flow case).
- The ambient temperature surrounding the solar cells is set to 25°C.

3. RESULTS AND DISCUSSION

Fig. 2 shows the ray tracing simulation of a Fresnel-based HCPV system; rays are distributed uniformly and equally across all four MJ cells outlets after passing the entire optical system. The thermal model's validity was verified by comparing it with the available data in the literature. Fig. 3 shows that the cell's temperature can reach up to 669°C, which agrees with the literature, as it has been reported that surface temperature can reach 1,200°C in 3 × 3mm^2 MJ solar cells with a CR of 400X and without a cooling system [13].

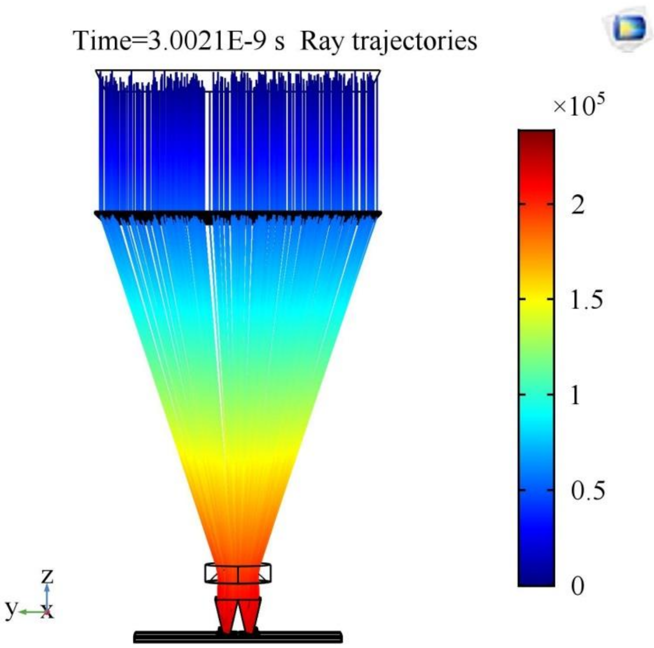

Fig. 2. Ray trajectory from the source of the light passing the entire optical system to solar cells

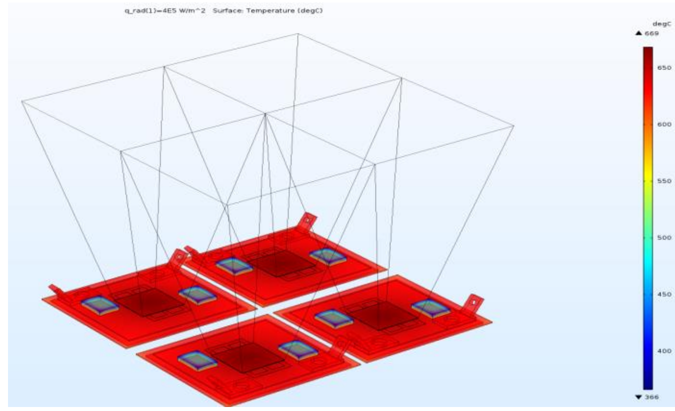

Fig. 3. Temperature distribution for solar cells without cooling system.

Increasing the inlet water velocity rate inside the cooling channel has been investigated (Fig. 4). An inlet water velocity ranging 0.01–0.4 m/s with a step of 0.05 was applied to the simulated system at different CR, and the cell temperatures were predicted with the aim of remaining below the operational limit temperature (i.e. 80°C). Fig. 4 shows that active cooling with a moderate inlet water velocity of 0.01 m/s can decrease the solar cells temperature under the operating limit temperature for the CR range of 200–600X, and the inlet water velocity of 0.05 m/s can maintain the maximum solar cells surface temperature within the operating limit for a CR of 800X. However, the high CR of 1000X needs an inlet water velocity of 0.3 m/s to keep the maximum solar cells temperature under the operating limit temperature.

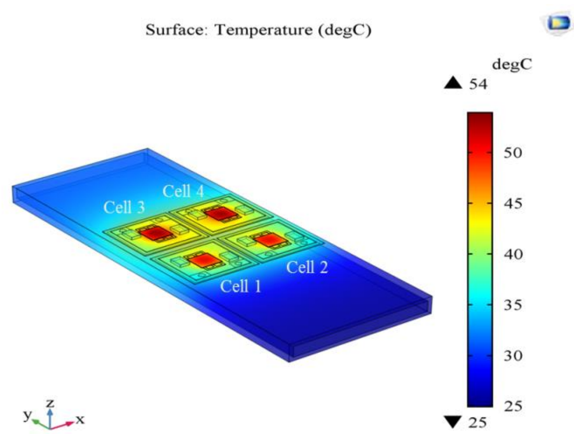

Fig. 5. Temperature distribution for solar cells of a single CPV after cooling (at U=0.01 and CR 300)

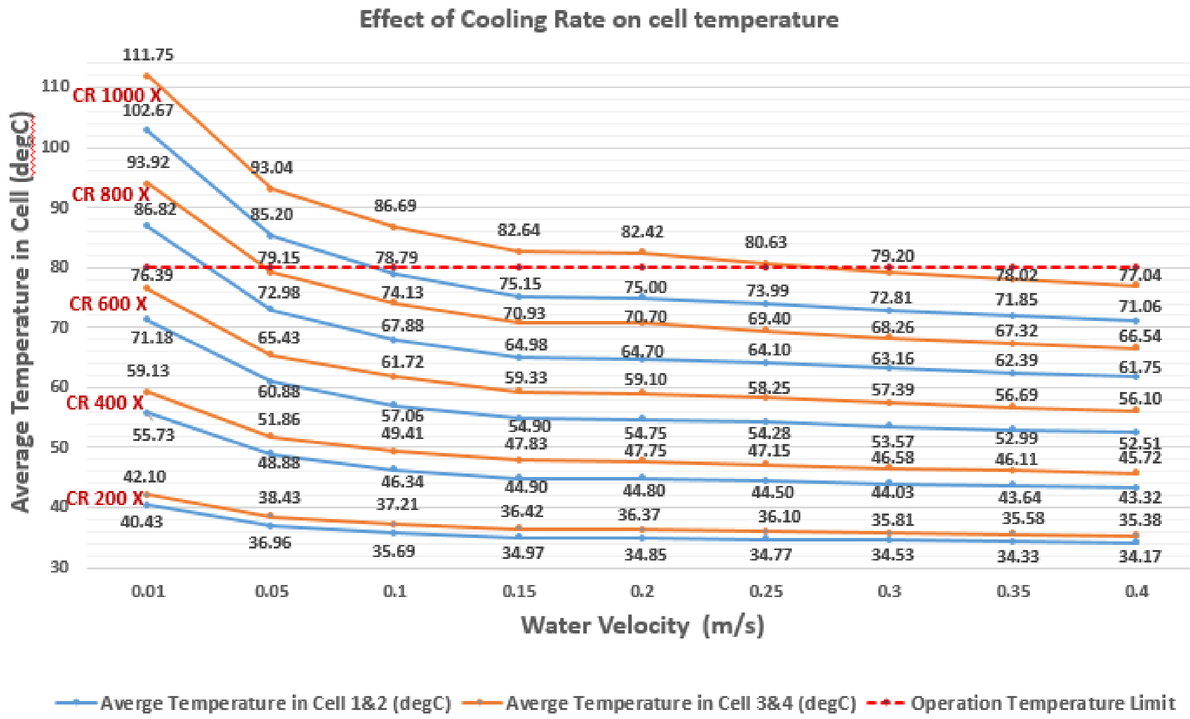

Fig. 4. Average solar cell temperature of a single CPV at differnet CRs and inlet water velocities

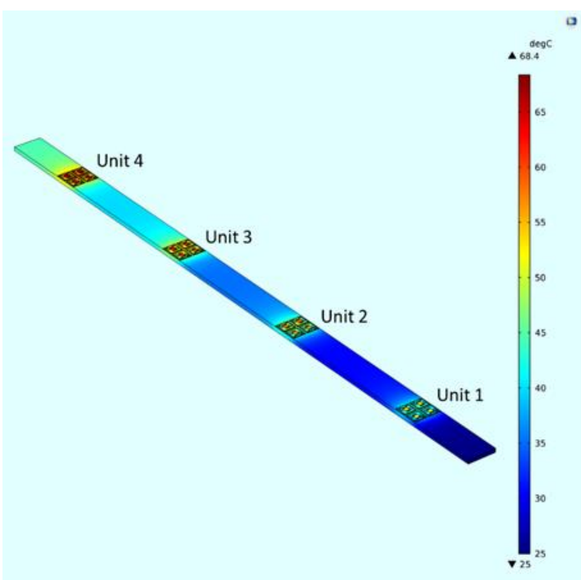

Fig. 6. Four CPV units' temperature profiles at 25°C ambient temperature

Fig. 6 shows the temperature distribution for four CPV assemblies with geometric CRs of 400X placed on one cooling channel with an inlet water velocity of 0.01 m/s. The distance between the centres of each two assemblies is the width of the Fresnel lens (i.e. 0.4 m), while the total length of the cooling channel is 1.6 m. The thermal modelling assumptions are the same as in methodology section, and the optical efficiency for the CPV system is considered 75%. Therefore, the heat flux on the MJ cell is equal to 300W/m2. Fig. 6 shows that the maximum solar cell surface temperature reaches approximately 68°C, which is less than the maximum operating temperature.

Fig. 7 shows the water temperature along the cooling channel for the CPV system shown in Fig. 6. As the number of CPV assemblies increases, so does the cooling water temperature. With four CPV assemblies and a CR of 300X, the average outlet water temperature is raised by almost 20°C (i.e. from 25°C to 44°C); this raises to 62°C with a CR of 600 X.

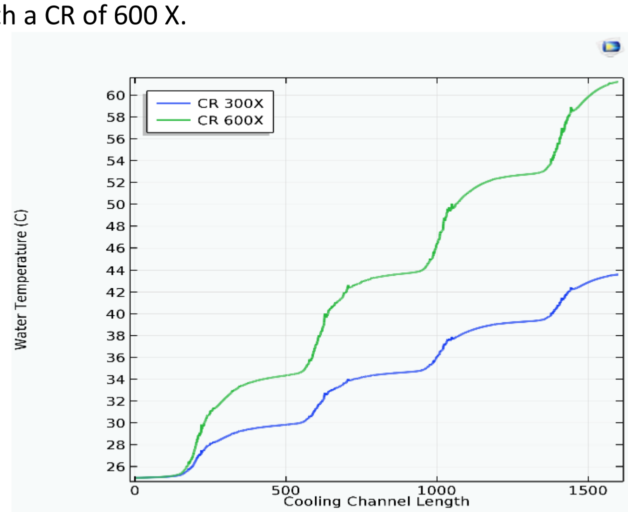

Fig. 7. Four CPV units' outlet water temperature along the cooling channel

4. CONCLUSIONS

This study developed a 3D thermal model for an assembly of four MJ solar cells with a Fresnel-based HCPV/T system and investigated the use of active cooling techniques to maintain MJ solar cells under the recommend operating limit of 80°C. The thermal performance of a Fresnel-based HCPV system integrated with the cooling channel system was investigated at different CRs and inlet water velocities. It was determined that as cooling water velocity increases to reach turbulent flow, higher CRs can be applied before reaching the maximum operating temperature for the MJ cells. At a CR of 1000X and a water velocity of 0.3 m/s, a maximum cell temperature of 79.2°C can be achieved, which is below the maximum operating temperature. Additionally, it was demonstrated that the cooling water temperature increases with the number of CPV assemblies. With four CPV assemblies at CR = 300X, the outlet water average temperature is raised from 25°C to about 44°C; when at CR = 600X, this average temperature is increased to 62°C .

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