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Solar Spectrum Dependent Thermal Model for HCPV Systems

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Abstract

Finite Element Analysis (FEA), is used to predict the thermal behaviour of a 2D model of a multi-junction solar cell in steady-state. An analytical solar spectrum dependent electrical model was used to quantify the thermal power which needs to be dissipated by the candidate cooling system. The heat losses are also accounted through three different mechanisms; conduction, natural convection and surface to ambient radiation. The results report on the maximum level of the cell's surface temperature and the heat transfer coefficient which is needed to keep the cell's temperature below 80^{o}C based on the worst case scenario for the specific multi-junction cells. In this study, the produced current density and voltage is calculated for each layer, thus, the exact thermal power can be quantified giving a more accurate prediction, resulting to a better estimation of the cooling requirements of the system. This is very critical for systems with high concentration ratios, especially in regions where the ambient air temperature is high. The results show that the analytical model gives a realistic prediction of the thermal power which passes through each layer of the III-V cell due to its ability to include the current mismatch and the infrared light absorption rate.

Keywords: Concentrating Photovoltaics, Solar Spectrum, Thermal-Electrical Modelling

1 Introduction

Concentrating Photovoltaics (CPV) use cheaper materials such as mirrors or lenses to focus direct sunlight onto a receiver, in order to increase the power output and reduce costs. In high concentrations (>400x), high efficiency multijunction solar cells can be used to further increase the power output.

Multijunction (MJ) solar cells are made of III-V compound semiconductors and are widely used in space and terrestrial applications. Currently the state-of-art solar cell on the market is the lattice matched III-V cell made of GaInP/GaInAs/Ge [1, 2]. The 3 cells are serially connected in such a way as to absorb a wider part of the solar spectrum beginning from the shorter wavelengths (top cell) to the longer wavelengths (bottom cell). Hence, a higher efficiency can be achieved, especially when compared to the single junction silicon cells (Figure 1). To date, the highest recorded efficiency for a 3 junction solar cell is 44% [3].

However, in High Concentrating Photovoltaic systems, due to the high heat flux concentration, the cell's surface temperature rises sharply resulting to suboptimal performance and increasing the risk of system failure. Cooling technology is therefore needed, to increase electrical conversion efficiency and potentially harness waste heat. In order to choose a cooling device for any CPV system, an accurate thermal model is required to quantify the thermal power which should be dissipated. Current thermal models use various assumptions such as a constant Direct Normal Irradiance (DNI), based on the integral of the reference spectrum [5] and equal to approximately 900W/m^2 for the air-mass 1.5 direct

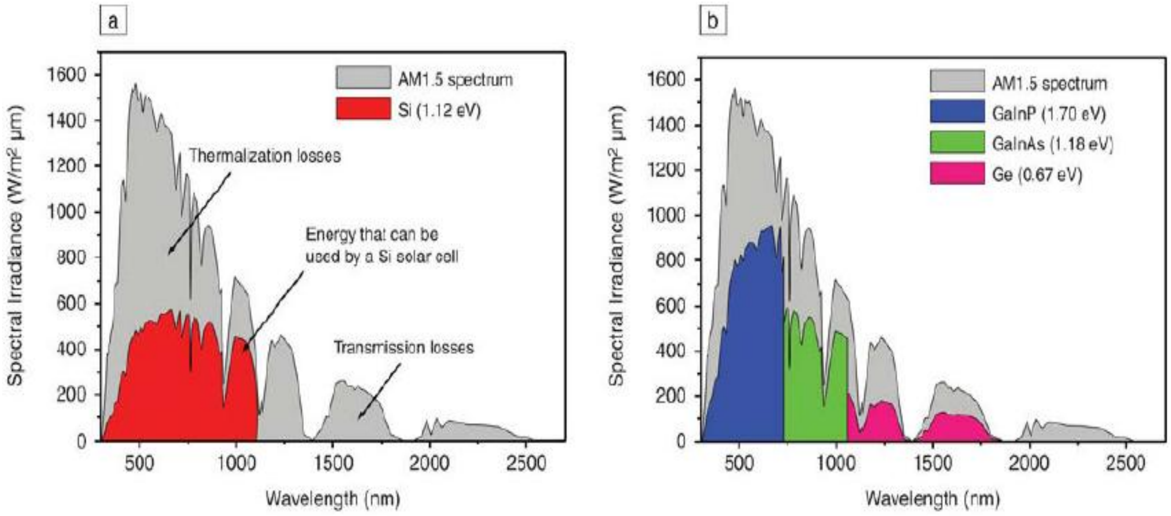


Figure 1: The AM1.5D solar spectrum and the parts of the spectrum that can, in theory, be used by: (a) Si solar cells; (b) GaInP/GaInAs/Ge solar cells [4].

(AM1.5D). Since the solar spectrum is transient through the day and solar cells or junctions (in the case of multi-junction cells) have different spectral responses, a more accurate model is required to achieve better accuracy. There also exists a limitation relating to the in-series connection of solar cells; a mismatch in the current produced by each cell will limit the overall output to the lower value resulting to higher thermal power from the receiver. Therefore, by applying a DNI value as an input in the thermal models, will only give an indication of the thermal behaviour at low accuracy; this is especially the case where a multi-junction solar cell is used due to its sensitivity to spectral balance.

In this study, a thermal model uses inputs of the solar spectrum dependent electrical model in order to investigate different cooling mechanisms using the convective heat transfer coefficient as a criterion. The first section describes the approach and gives the equations used for both models, while in sections three and four, the electrical and thermal models are described and the results are discussed.

2 Approach

The first step of this investigation was to model the electrical behavior of a III-V MJ solar cell. The AZURSPACE 3C40A [5] was selected for the needs of this study.

2.1 Electrical Model

The External Quantum Efficiency (*EQE*), defined as the ratio of the number of electrons generated by the cell to the number of incident photons, characterised by the manufacturer, was used to calculate the solar cell response. As an input for the model, the AM1.5D solar spectrum was taken from the NREL SMARTS model [6]. Assuming that the solar spectrum is uniformly concentrated on the solar cell's surface, all the values of the DNI were multiplied by the Concentration Ratio (CR) of 500x.

The short-circuit current density as a function of wavelength was then calculated using equation 1:

$$J_{sc} = \int_{280}^{\lambda} \frac{q \cdot \lambda \cdot EQE(\lambda) \cdot \eta_{opt}(\lambda) \cdot G(\lambda)}{h \cdot c} \cdot d\lambda \quad (1)$$

where q is the elementary charge, λ the wavelength of photons, $\eta_{opt}(\lambda)$ the optical efficiency as a function of wavelength (assumed to be a unity), $G(\lambda)$ is the DNI as a function of the wavelength, h is Planck's constant and c the speed of light in vacuum.

The open circuit voltage was calculated using:

$$V_{oc} = \frac{k \cdot T}{q} \ln\left(\frac{I_{sc}}{I_o} + 1\right) \quad (2)$$

where k is Boltzmann's constant, T is the cell's temperature and I_o the dark saturation current.

The I-V curves of the solar cells where simulated using the diode law:

$$I = I_o \cdot \left[\exp\left(\frac{q \cdot V}{n \cdot k \cdot T} \right) - 1 \right] - I_L \quad (3)$$

where n is the diode ideality factor and I_L is the photogenerated current which is nearly equal to the short-circuit current.

2.2 Thermal Model

The conjugate heat transfer interface of COMSOL Multiphysics was used to model the thermal performance of the HCPV cell. This interface has the advantage of combining both heat transfer in solids and fluids including laminar or turbulent flow simultaneously.

A schematic of the HCPV model is shown in Figure 2. Direct solar radiation is collected by a primary concentrator and a secondary reflector is used for homogenization purposes. The solar cell is attached to a heat sink to enhance heat dissipation. The heat is transferred by conduction between the solid layers of the receiver. The solar energy that is transformed to heat must be dissipated from the bottom substrate or cooling system to the environment or to another unit. Some heat is lost to the environment, due to natural convection from all free surfaces. COMSOL Multiphysics uses different heat transfer correlations for each surface orientation; these can be found from Incropera and DeWitt [7].

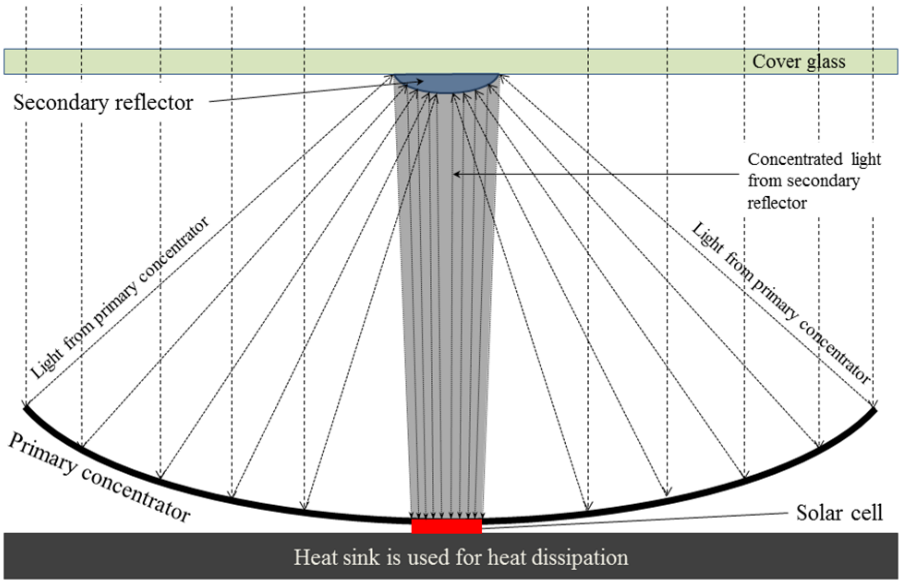


Figure 2: Schematic of the HCPV system for thermal modeling.

3 Electrical Model

The EQE response of the AZURSPACE 3C40A and the AM1.5D from the NREL SMARTS model multiplied by a CR of 500x are shown in Figure 3.

By using equation (1) the short-circuit current density for each cell was calculated as a function of wavelength and can be seen in Figure 4. From Figure 4 it is obvious that the bottom cell (Germanium) generates higher current. Due to the nature of series connections, the total current output of the cell will be restricted to the minimum value of the 3 sub-cells while the voltage is summed. This has a significant impact on the electrical performance of the cell since the excess current will be transformed directly to heat.

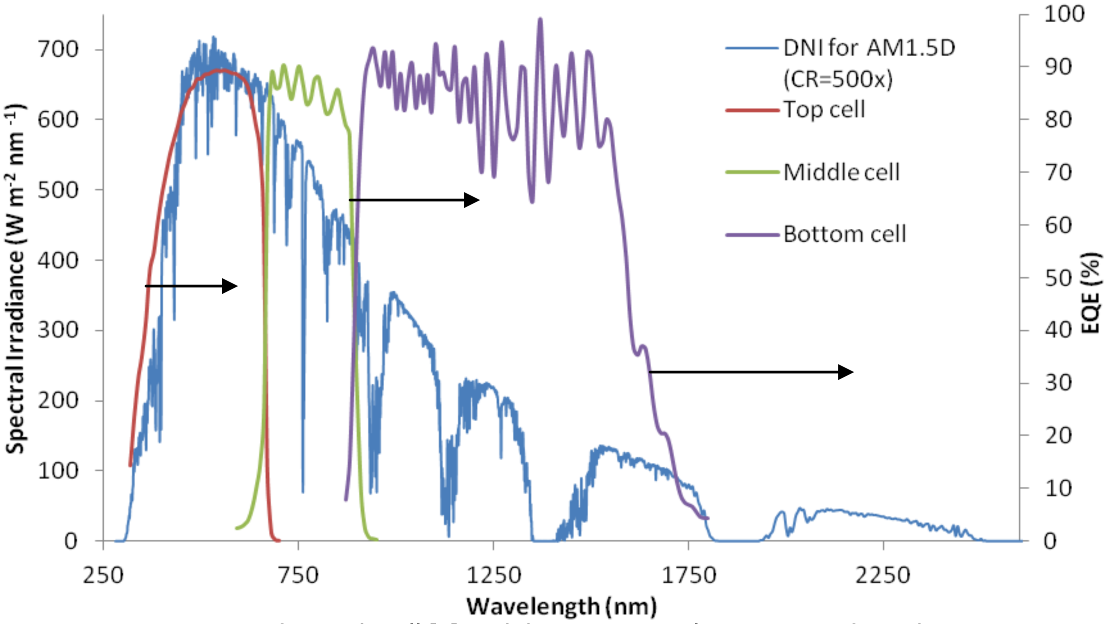


Figure 3: EQE response for each cell [5] and the AM1.5D solar spectrum from the NREL SMARTS model multiplied by a CR of 500x.

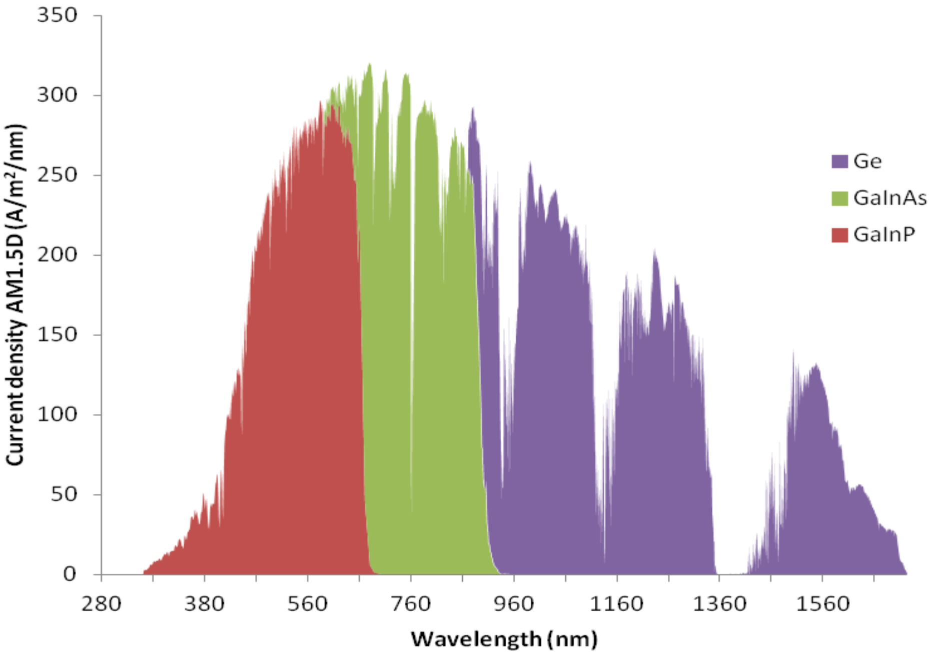


Figure 4: Short-circuit current density for each layer as a function of wavelength.

In Figure 5, the I-V curves were plotted for each sub-cell using the assumptions from Table 1. It can be noticed that the excess current from the Germanium (green curve) is relatively much higher than the other 2 sub-cells which are current matched. The maximum electrical output power from the cell was found to be 18.55W while the minimum heat power which needs to be dissipated is 26.45W.

Table 1: Assumptions used for the electrical model.

Subcell	Diode ideality factor (*n*)	Dark current density (*Jo*)
GaInP	1.45	10^{-19} A/cm^2
GaInAs	1.13	10^{-17} A/cm^2
Ge	0.36	10^{-15} A/cm^2

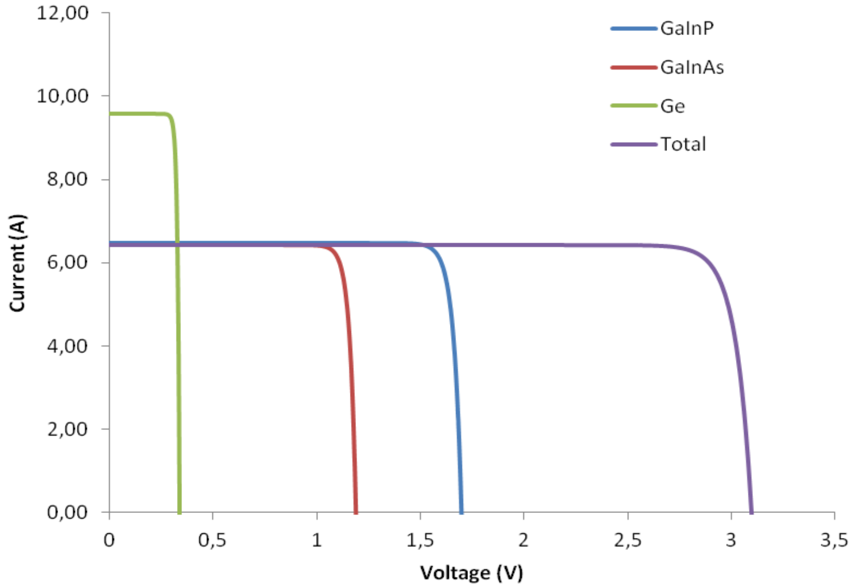


Figure 5: I-V curves for each sub-cell and total.

4 Thermal Model

Having calculated the heat power from the solar spectrum dependent electrical model the next step was to apply the values in the thermal model.

The geometry and thermal boundary conditions of the model are shown in Figure 6 and Table 2. Also, the dimensions and thermophysical properties of the materials used in the 2D model are shown in Table 3 and 4 respectively. The solar cells are attached on the substrate which is made of copper and Al_2O_3 ceramic with an adhesive material. For simplicity, the bypass-diodes, electrical connections and packing materials are not modelled.

The model applies an inflow heat flux on the cell, while the bottom and top surface release heat to the environment through natural convection and radiation (surface to ambient). The left and right boundaries of the fluid are set as 'open boundaries'. The volume force of the fluid is $F_y=-g(\rho_\infty-\rho)$ [N/m^3].

Table 2: Thermal boundary conditions.

No	Region	Boundary condition
1	Back side of cell	Inflow heat flux as found from electrical model
2	Air gap	Open boundary conditions with no shear stress
3	Cell's surface	Surface to ambient radiation and natural convection
4	Sides of cell	Perfect thermal insulation was assumed on the sides of the cell and a no slip boundary condition was considered on the wall
5	Back plate	Surface to ambient radiation and convection
6	Air gap	Ambient temperature of 20-45^{o}C

Table 3: 2D model dimensions.

Layer	Length [mm]	Thickness [mm]
GaInP	10	0.1
GaInAs	10	0.2
Ge	10	0.2
Adhesive Material	10	0.1
Copper	30	0.3
Al_2O_3 Ceramic	30	0.63

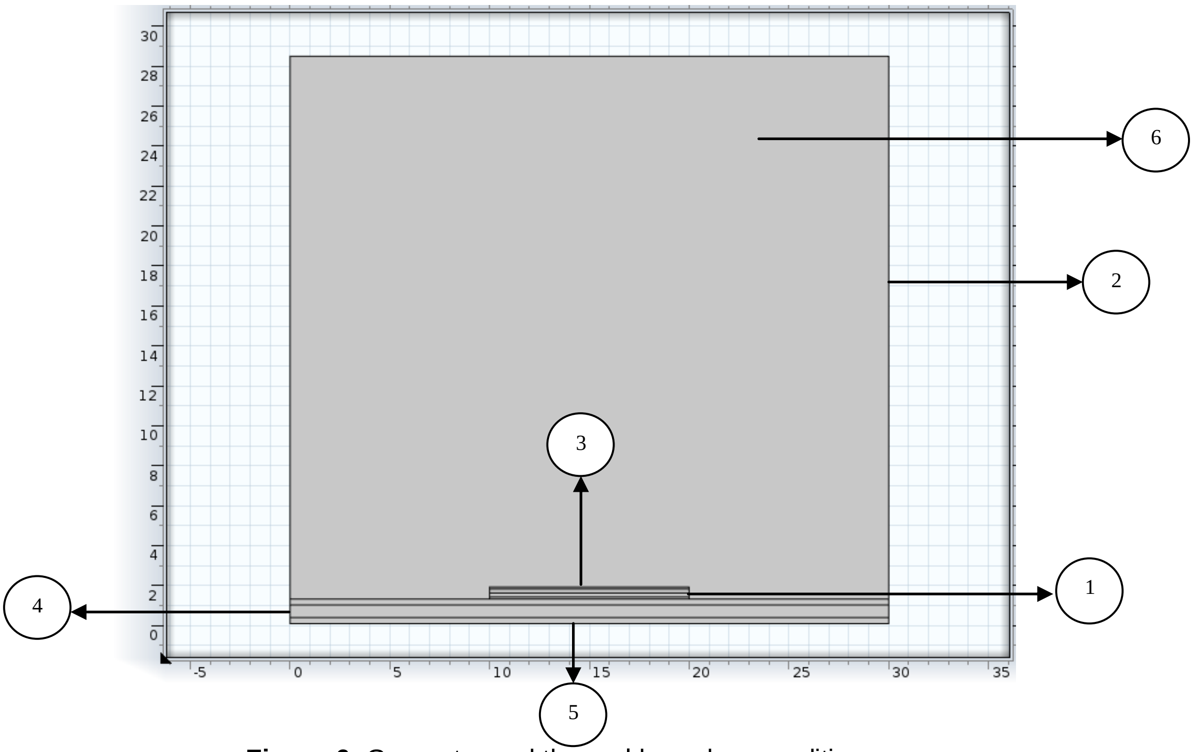


Figure 6: Geometry and thermal boundary conditions.

Table 4: Materials' thermophysical properties.

Layer	***k* [W/mK]**	***Cp* [J/kgK]**	***ρ* [kg/m³]**
GaInP	73	73	5300
GaInAs	65	550	5316
Ge	60	310	5323
Adhesive Material	10	800	4000
Copper	401	385	8933
Al_2O_3 Ceramic	20	880	3700
Aluminum	238	903	2702

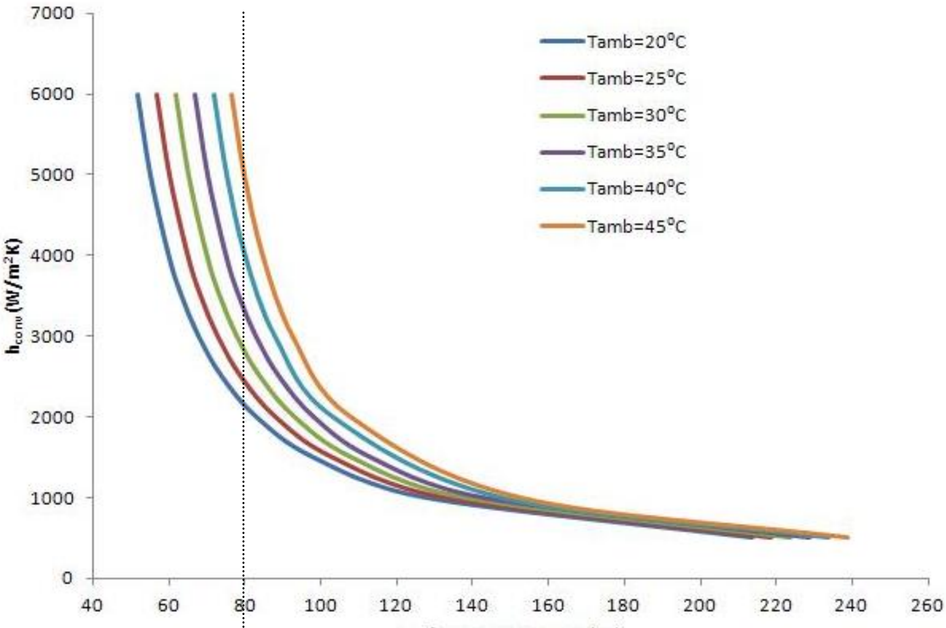
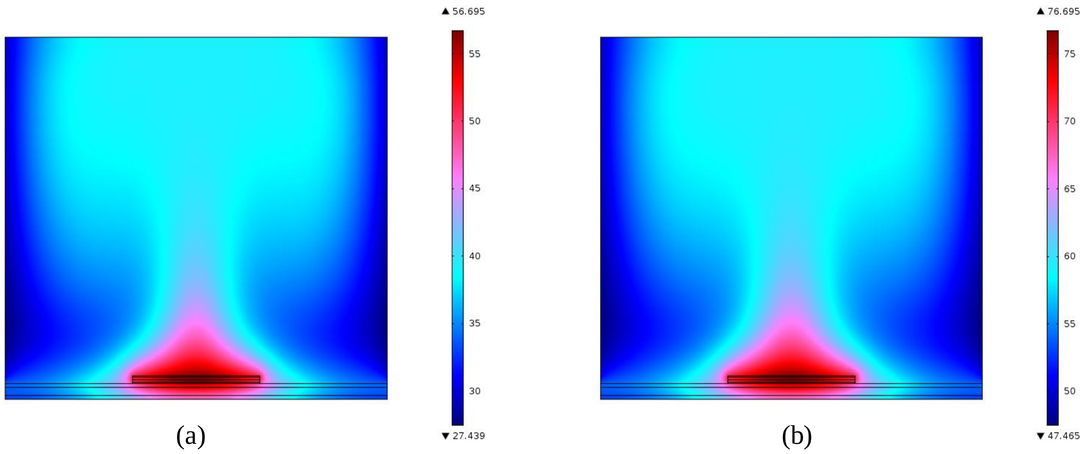


Figure 7: Cell's surface temperature for $500 W/m^2K \leq h_{conv} \leq 6 kW/m^2K$ and $20^oC \leq T_{amb} \leq 45^oC$.



(a) (b)

Figure 8: Temperature distribution for h_{conv} = 6kW/m^{2}K and (a) T_{amb} = 25^{o}C; (b) T_{amb} = 45^{o}C.

The simulations were conducted in steady state. The convective heat transfer coefficient from the back plate was varied from 500W/m^{2}K to 6kW/m^{2}K with a step of 500 and for ambient air temperature from 20^{o}C to 45^{o}C (Figure 7). Solar cell manufacturers suggest that the cells should not operate on temperatures higher than 80^{o}C.

Figure 7 shows the results of the simulations. It is clear that a minimum heat transfer coefficient of 2.5kW/m^{2}K is required from the cooling system in order to maintain a temperature below 80^{o}C, under a CR over 500x. However, considering that CPV systems are installed in regions with high DNI, thus high ambient air temperatures (over 40^{o}C), a h_{conv} higher than 2.5kW/m^{2}K will be needed.

Figure 8 shows the temperature distribution across the solar cell receiver for a h_{conv} = 6kW/m^{2}K and two different values of ambient air temperature, 25^{o}C and 45^{o}C. A maximum solar cell's surface temperature of 76.7^{o}C and 56.7^{o}C is predicted under 45^{o}C and 25^{o}C of ambient temperature respectively. Although, the electrical power decrease with increasing temperature is not accounted in this case, thus higher thermal power to be dissipated, it can be concluded that CPV installations in regions with high ambient temperature should consider a minimum heat transfer coefficient of 6kW/m^{2}K.

5 Discussion and Conclusions

A detailed integrated solar spectrum dependent thermal-electrical model was described for a HCPV cell. This model can lead to the accurate quantification of the thermal power which is needed to be dissipated, including the excess thermal output due to current mismatch.

It is concluded that passive cooling cannot dissipate enough heat from the cell since a minimum convective heat transfer coefficient of 2.5kW/m^{2}K is needed from the candidate cooling system. Also, considering that the current project's design will be installed in India, where high ambient air temperature over 40^{o}C can occur, it can be confidently said that passive cooling would be catastrophic for the installation.

This study confirms the results of our previous paper in [8], where real meteorological data were used to predict the temperature distribution across a solar cell and was suggested that a h_{conv} of around 6kW/m^{2}K should be required from the cooling system in order for the cell to withstand the harsh ambient conditions.

A more detailed study using an active cooling device is part of the future work along with experimental validation of the models.

Acknowledgment

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