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3D Thermal Numerical Analysis of a Densely Packed Concentrating Photovoltaic Receiver

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Abstract: This paper presents a three-dimensional numerical model that has been developed to predict the thermal behaviour of a high efficiency solar cell receiver under various conditions. Real-time meteorological data are used to calculate the heat transfer coefficient required to maintain the solar cell's temperature below 80°C. An extended aluminium surface (heat sink) was designed and applied on the back of the receiver to increase heat removal by passive cooling. It is shown that passive cooling in densely packed geometries can only be feasible for concentrations below 60 suns. A minimum convective heat transfer coefficient of $3.5W/m^2K$ was found to satisfy the cooling requirements when solar radiation is concentrated by a factor of 500x, for an ambient temperature of less than 25^oC. It is concluded that densely packed solar cell receivers require active cooling in order to operate safely, without the risk of complete failure in the field.

Keywords: Concentrating Photovoltaics, Thermal Modelling, Heat Transfer Coefficient, Natural Convection

1. INTRODUCTION

This research is part of a larger project, BioCPV, which will develop and integrate the use of Concentrating Photovoltaics (CPVs) with Biomass and Hydrogen generation to help to reduce the urban and rural energy divide in India. In particular, this paper deals with the thermal modelling of a densely packed configuration of a CPV system which is currently under construction in the laboratory facilities of Heriot-Watt University.

CPV systems use cheap optics such as mirrors and lenses to focus direct solar radiation onto a smaller area of solar cells (i.e. the receiver). This allows the replacement of the high cost solar cells with cheap optics in order to have the same electrical power output. CPV's therefore provide an opportunity to use highly efficient (>30%) multijunction (MJ) cells which are more expensive than conventional PV cells. The use of MJ cells can only be economically viable if high concentration solar flux, above 300 suns, is produced [1].

However, while the concept of this technology is straightforward, the practice has proved deceptively difficult. The main technical barrier is the high surface temperature on the cell which leads to reliability issues as well as a reduction in the conversion efficiency of the cell [2]. The PV cell's efficiency drops with increasing temperature caused by the high heat flux from the solar source and relatively high ambient air temperatures. Also, if the cell operates above a design temperature, specified by the manufacturer limit (80^oC for AZURSPACE GMBH [3]) the cells will exhibit long-term degradation [4]. Therefore, under high concentration a considerably higher heat load needs to be dissipated.

The first challenge in generating electricity efficiently is to effectively cool the cells to allow peak performance in all conditions. A second challenge, although not part of the current investigation, will be to take advantage of the "waste heat" to improve the overall system efficiency. If this can be achieved it will lead to more economical, efficient and reliable CPV systems.

2. METHODOLOGY

In this work, a densely packed receiver cell is evaluated using Finite Element Analysis (FEA) in COMSOL Multiphysics [5], a commercially available software. COMSOL Multiphysics offers the possibility to combine different engineering or physical problems in the same model while being able to choose different solvers in order to achieve better accuracy. Another advantage is that it gives the option to import data from MatLAB and Microsoft Excel.

2.1 Problem quantification

The first step of this investigation was to predict the minimum heat transfer coefficient that is needed to keep the temperature of a single cell below 80°C. Hourly meteorological data from Athens which has a similar climate, in terms of direct solar radiation and ambient temperature, to that of the proposed location of the eventual power plant near Kolkata, India has been used in this study for a period of one year. Assuming that the cell's electrical efficiency is constant at 38% it was found that a heat transfer coefficient higher than 6kW/m^{2}K is needed from the cooling system.

The electrical power flux for each hour of the year (j) is calculated from the equation:

$$q_{elec}(j) = CR \cdot n_{optical} \cdot q_{solar}(j) \cdot n_{elec} \tag{1}$$

where *CR* is the geometrical concentration ratio of the system (500x), $q_{solar}(j)$ is the hourly direct radiation from the sun (W/m^2), $n_{optical}$ the optical efficiency of the system (~85%) and n_{elec} equals to 38%.

The heat flux absorbed by the receiver equals to:

$$q''_{heat}(j) = (CR \cdot n_{optical} \cdot q_{solar}(j)) - q_{elec}(j) \tag{2}$$

where $q''_{heat}(j)$ is the amount of heat flux that has to be anticipated by the cooling system.

The heat transfer coefficient needed for each hour of the year is calculated from equation below and it is shown graphically in Fig. 1:

$$h(j) = \frac{q''_{heat}(j)}{T_{surface} - T_{ambient}(j)} \tag{3}$$

where $T_{surface}$=80°C. It is apparent, that very high rates of heat flux occur, especially during the summer period. Consequently, a high heat transfer coefficient from the cooling system is required, in order to keep the system working without the risk of degradation.

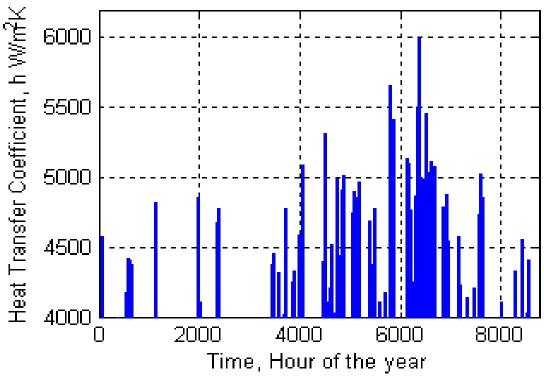

Fig. 1: Heat transfer coefficient needed for a maximum cell surface temperature of 80°C.

2.2 COMSOL Multiphysics model

The heat transfer interface of COMSOL Multiphysics was used to model the thermal behaviour of a densely packed HCPV module.

A schematic of the model is shown in Fig. 2. The heat is transferred by conduction between the solid layers of the receiver. The solar energy which is transformed to heat must be dissipated from the aluminium heat sink as shown in the figure. Some heat is lost in 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 [9].

The geometry and thermal boundary conditions of the numerical model as imported in the software are shown in Fig. 3 and Table 1. Also, the dimensions and thermo-physical properties of the materials used in the 3D model are shown in Table 2 and 3 respectively. Twenty five multi-junction solar cells (GaInP/GaInAs/Ge) are used in the model and are attached on the substrate which is made of copper (for heat dissipation) and Al_2O_3 ceramic (for electrical insulation) with an adhesive material. For simplicity, the bypass-diodes, electrical connections and packing materials are not modelled.

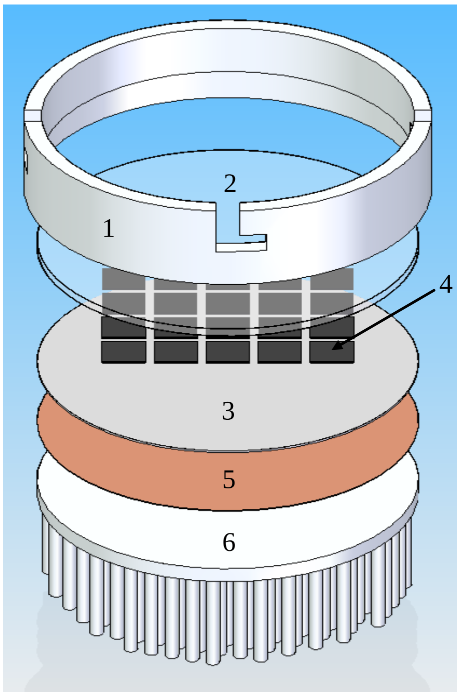

Fig. 2: PV receiver components
1: Frame, 2: Cover glass, 3: Al_2O_3 ceramic, 4: Solar cells, 5: Copper plate, 6: Aluminium heat sink

Table 1: Thermal boundary conditions.

No	Region	Boundary condition
1	On top of cells	Inflow heat flux as found from numerical model
2	Ambient	Ambient temperature of 20-45°C
3	Cell's surface	Surface to ambient radiation and natural convection
4	Sides of cell	Heat is conducted through the layers
5	Heat Sink	Surface to ambient radiation and convection

Table 2: 3D model dimensions.

Layer	Length [mm]	Width [mm]	Thickness [mm]	Diameter [mm]
GaInP	10	10	0.1	n/a
GaInAs	10	10	0.2	n/a
Ge	10	10	0.2	n/a
Al_2O_3 Ceramic	n/a	n/a	0.63	88
Copper	n/a	n/a	0.3	88

Table 3: Materials' thermo-physical properties.

Layer	*k* [W/mK]	*Cp* [J/kgK]	ρ [kg/m^3]
GaInP	73	73	5300
GaInAs	65	550	5316
Ge	60	310	5323
Al_2O_3 Ceramic	27	900	3900
Copper	400	385	8700
Aluminum	160	900	2700

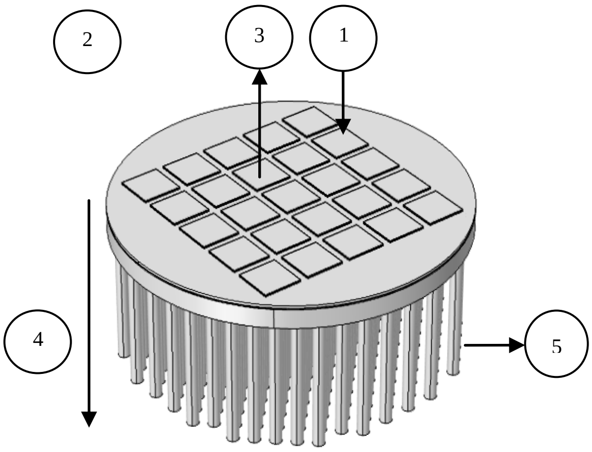

Fig. 3: Geometry and thermal boundary conditions.

The model applies an inflow heat flux on the cells, while the bottom and top surfaces release heat to the environment through natural convection and radiation (surface to ambient).

A multi round pin aluminium heat sink similar to those who are used for passive cooling of LEDs was used since the future electrical characterisation will take place under 1 sun conditions, for validation purposes. This heat sink includes 221 fins (pins), each one of them is 30mm height and 3mm diameter. The heat sink's plate has a diameter of 88mm and 4.5mm thickness.

3. RESULTS AND DISCUSSION

The simulations ran using the solver algorithm GMRES (Generalized Minimum RESidual) which is a linear system solver. Two geometries were investigated, one including an extensive surface (heat sink) and one without. The simulations including the heat sink were conducted in steady-state using parametric studies for concentrations from 50 to 500 suns, ambient temperature from 20 to 45°C and heat transfer coefficient on all free surfaces between 5-25W/m^{2}K. The geometry without heat sink was simulated using a steady-state parametric study for a heat transfer coefficient on the bottom layer between 500 to 7500W/m^{2}K. Both geometries were meshed using a finer mesh on the solar cells and normal mesh on the rest surfaces. The temperature profiles of the receiver and heat sink are obtained solving momentum, mass and energy equations.

The results in Fig.4 show the maximum temperature of the solar cell as a function of a heat transfer coefficient. This coefficient was applied on all the free surfaces of the geometry to demonstrate the natural convection. It can be seen that passive cooling is not capable to dissipate enough heat from the system while in Fig. 5, the effect of the ambient air temperature is shown. Fig. 6 shows the solar cell's temperature under various geometrical concentrations. Densely packed geometries can be cooled passively only if the geometrical concentration does not exceed the 60 suns.

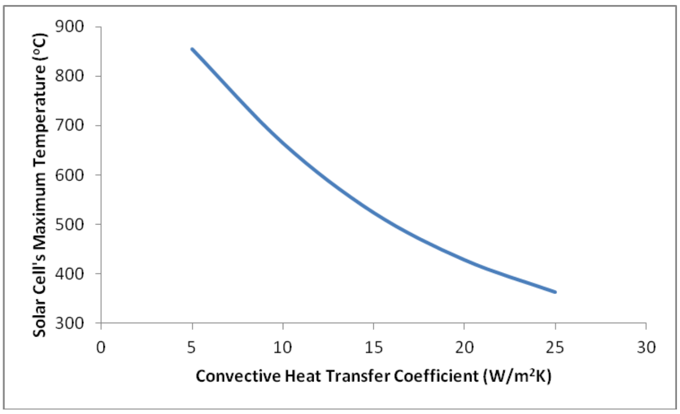

Fig. 4: Solar cell's maximum temperature versus the natural convective heat transfer coefficient under 500x suns and 25°C of ambient temperature.

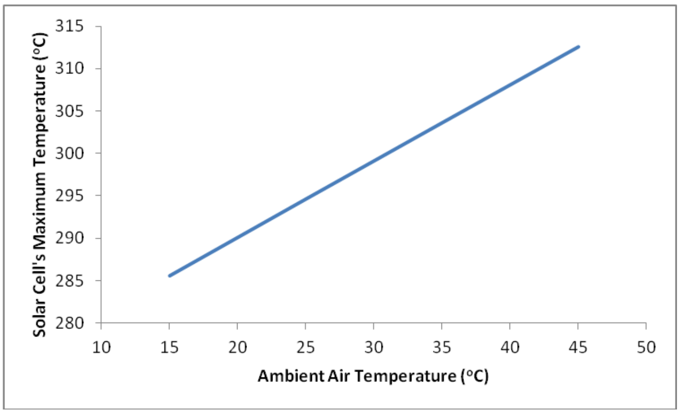

Fig. 5: Solar cell's maximum temperature as a function of the ambient air temperature and a convective heat transfer coefficient of $15 W/m^2K$ and geometrical concentration ratio of 500 suns.

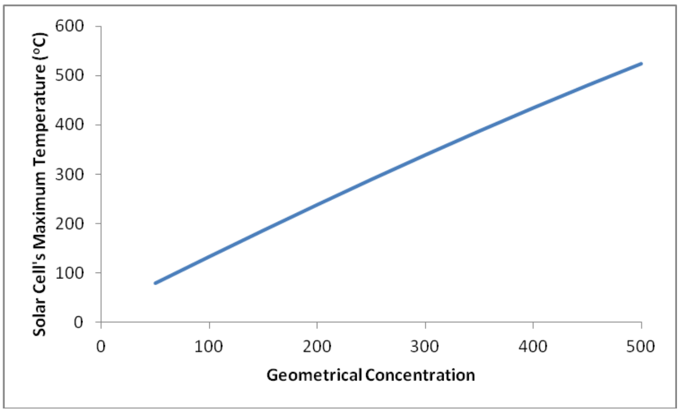

Fig. 6: Solar cell's maximum temperature as a function of the geometrical solar concentration and a convective heat transfer coefficient of $15 W/m^2K$ and 25^oC of ambient temperature.

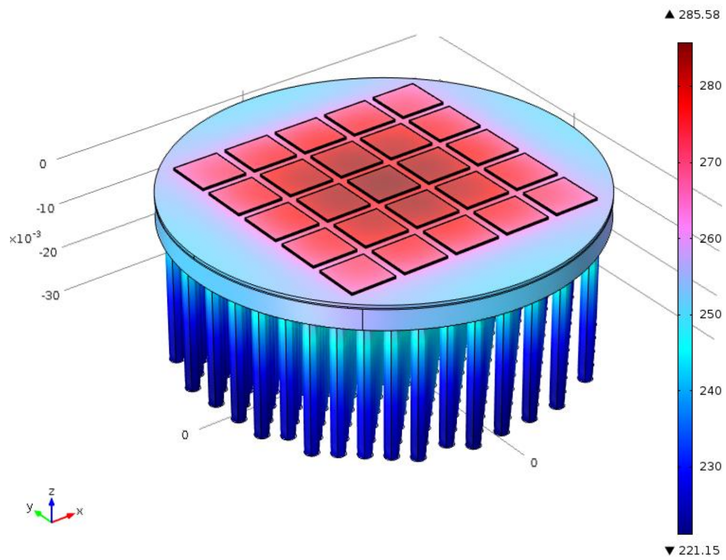

Fig. 7: Temperature distribution (^oC) of the densely packed receiver under 500x concentration, convective heat transfer coefficient of $15 W/m^2K$ and ambient air temperature of 15^oC.

Fig. 7 illustrates the temperature distribution of the geometry. From the figure, the concentrated solar radiation which is reflected on the surface from the optical components, can be characterised by the Gaussian distribution. A maximum solar cell temperature is shown to be 285.58^oC. However, the simulation without any extended surface, showed a significant decrease on the cell's surface temperature when a forced convection heat transfer coefficient was applied on the bottom layer (copper plate). The temperature distribution can be seen in Fig. 8 while Fig. 9 shows the solar cell's temperature as a function of heat transfer coefficient between 500W/m^{2}K to 7.5kW/m^{2}K. It can be noticed that a heat transfer coefficient above 3.5kW/m^{2}K can maintain the cell below 80^{o}C, however this is the case when the ambient temperature is 25^{o}C. Fig. 5 shows that the ambient temperature increase has a significant effect on the cell's temperature. Therefore, when a CPV system is designed, a safety factor should be allowed, thus a higher heat transfer coefficient.

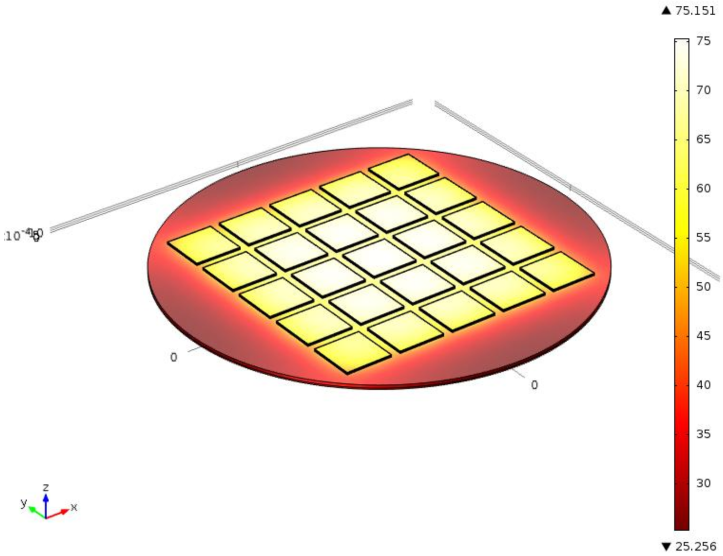

Fig. 8: Temperature distribution (^{o}C) of the densely packed receiver under 500x concentration, convective heat transfer coefficient of 3.5kW/m^{2}K and ambient air temperature of 25^{o}C.

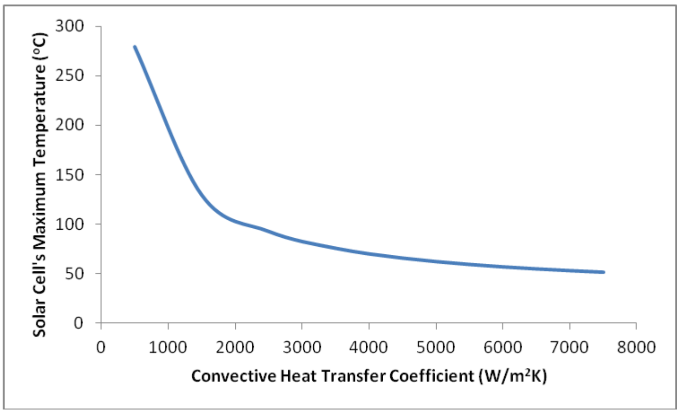

Fig. 9: Solar cell's maximum temperature versus the forced convective heat transfer coefficient under 500x suns and 25^{o}C of ambient temperature.

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