



## Heat Transfer in Spherical Micro Solar Cell Modules

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**Abstract.** Recently, spherical solar cells (SPVC) have drawn attention due to their low costs, flexibility, and efficiency: spherical reception surface can intercept sunlight in all directions thus increasing its power generation capacity. This paper reports a numerical analysis of steady state heat transfer from the SPVC to the ambient, unveiling the underlying paths and mechanisms. Within the limits of acceptable simplifying assumptions we define a sequence of 3D FEM models aimed at investigating the convective heat transfer processes: natural convection cooling and forced convection of a SPVC panel. The results may be used to optimizing the thermal design of SPVC modules.

### Key words

Photovoltaic cells, spherical cells, heat transfer, numerical simulation, finite element.

### 1. Introduction

Recent concerns about global warming, climate change, the prospect of exhaustion of fossil fuels and an imminent energy crisis, have prompted a growing interest towards alternative energy sources, and the direct conversion of solar radiation in electricity seems to be an ideal alternative. Currently, conventional solar cells with planar light reception surface are made of highly purified silicon crystals, which imply very high costs and complex production processes. The recent shortage of high-grade silicon has generated interest in developing alternative photovoltaic technologies. For instance, spherical solar cells (SPVC) have drawn attention due to their relative low costs (using less silicon), flexibility (adaptability of the solar modules to a variety of applications), and conversion efficiency: spherical reception surface can intercept sunlight in all directions, thus increasing its power generation capacity; it can minimize output fluctuations even under direct sunlight,

and even the angle of reflected incident light changes [1].

Thermal aspects have a great importance in the design of SPVC. The temperature rise in the SPVC panels, due to the inherent radiation losses and heat generation, is an important limiting factor. In order to provide for the thermal stability of SPVC panels, a detailed knowledge of the temperature distribution field is essential. This paper reports a numerical analysis of the steady state heat transfer under forced and natural convection conditions, unveiling the underlying paths and mechanisms.

We define a sequence of 3D numerical (finite element, FEM) models aimed at investigating the thermal regime of a SPVC panel cooled by both natural and forced convection. The results describe the heat transfer mechanisms and the thermal loads experienced by the PV system. This study may be relevant in the design phase of building integrated PV (BIPV) applications [9], not only as active components (energy generators), but also as passive transparent building elements (façades, windows and semi-transparent roofs) capable not only of sparing energy, but also of a particular aesthetic value.

### 2. The Spherical Solar Cell – A 2D Model

The resistive heating (internal Joule losses) within the SPVC and the heat flux received from the Sun are the heat sources of concern in this study. First, the electrical field problem is solved. Then, resistive heating and the radiation heat flux fraction of the solar irradiance received by the cell are input to a heat transfer model aimed at studying the thermal load and hot spots in the SPV panel under standard working conditions.

The axial symmetry of the SPV bead suggests that a 2D model of the current distribution and heat dissipation may be satisfactorily accurate. We assume that the SPVC operates under DC conditions hence the associated

electrical field is potential. We also assume that the PV current generation occurs at the  $n$ - $p$  interface, and that the  $n$  and  $p$  layers are passive.

The mathematical model for the electrical field in the  $n$  and  $p$  regions of the SPVC and in the collector (metallic) region is described by Laplace equation,  $\Delta V = 0$ . The electrical conductivities of the collector and emitter are  $\sigma_p$ ,  $\sigma_0$  respectively. Ohm's law,  $\mathbf{J} = -\sigma_{0,p} \nabla V$ , relates the current density to the voltage, and  $w^m$  denotes the photovoltaic current source located at the  $n$ - $p$  interface (assumed uniform).

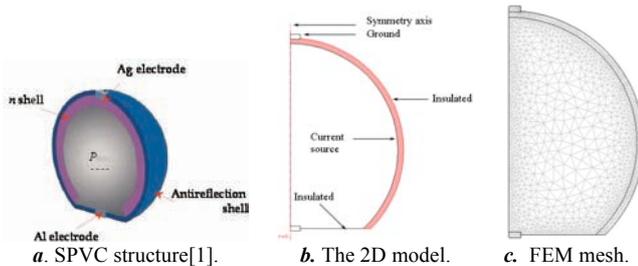


Fig.1 The spherical photovoltaic cell [2].

Figure 1 shows a sketch of the SPVC bead (a), the computational domain (b), and the FEM mesh (c). In this study we are modeling the short-circuit working condition of the SPVC [2]. The electrical problem inside the SPVC bead is divided into two coupled DC sub-problems, accounting for the two layers ( $n$  and  $p$ ).

Except for the output port, through which the current exits the cell, which is grounded, the boundary is assumed electrically insulated. The silver contacts that connect the bead to the collector grid are grounded.

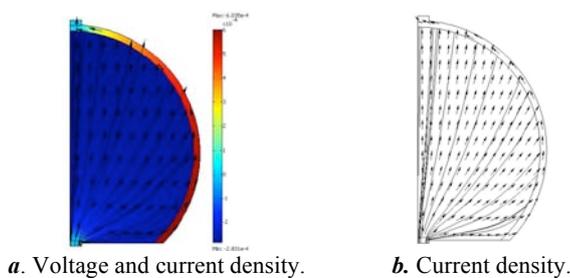


Fig.2 Electric field spectra.

The model was solved by FEM Galerkin technique [3, 4]. Numerical accuracy was checked against the current balance: the photovoltaic current equals the current delivered at the emitter-collector interface. Figures 2 a,b show the field spectra of the voltage (surface color map and contour lines), and the current density path (streamlines and arrows).

A constructal optimization [5, 6] of SPVC modules, aiming at minimizing the series resistance, was carried out and reported elsewhere [7].

### 3. Heat Transfer Models

The heat transfer analysis of SPV systems is complicated

because of the complex nature of the governing fluid flow and heat transfer mechanisms. The SPVC generates heat, and receives and conveys heat to the ambient through radiation and natural and (or) forced convection. We assume that heat transfer to the ambient is dominated by convection, and developed a model to investigate the paths and mechanisms of heat transfer and the thermal load within the SPVC structure, under standard heat transfer flow conditions to the environment (AM 1.5 spectrum,  $1000\text{W/m}^2$  solar irradiation,  $T_{cell} = 25^\circ\text{C}$ ).

The mathematical model that describes the weakly compressible, laminar air flow and heat transfer process is based on momentum (Navier-Stokes) balance equation (non-isothermal), the mass continuity law, and the energy equation in stationary forms [6]:

*Momentum balance (Navier-Stokes) (in the air domain)*

$$\begin{aligned} \rho(\mathbf{u} \cdot \nabla) \mathbf{u} &= \\ &= -\nabla p + \nabla \cdot [-p\mathbf{I} + \eta(\nabla \mathbf{u} + (\nabla \mathbf{u})^T) - 2\eta/3(\mathbf{u} \cdot \nabla)\mathbf{I}] \end{aligned} \quad (1)$$

*Mass conservation*

$$\nabla \cdot \mathbf{u} = 0, \quad (2)$$

*Energy Balance*

$$\nabla \cdot (-k\nabla T) = Q - \rho C_p \mathbf{u} \cdot \nabla T. \quad (3)$$

Here  $\mathbf{u}$  is the velocity field,  $p$  is pressure,  $\rho$  is the density of air,  $\eta$  is the dynamic viscosity of the air,  $k$  is the thermal conductivity,  $C_p$  the specific heat capacity, and  $Q$  the Joule effect (internal heat source)

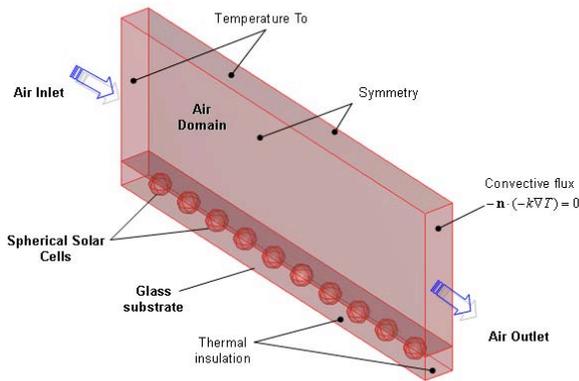
$$Q = \frac{1}{\sigma} |J|^2 = \frac{1}{\sigma} |\sigma E|^2 = \sigma |\nabla V|^2. \quad (4)$$

We used the fully compressible formulation of the continuity equation and momentum equations, where the stress tensor used in eq. (1) describes a Newtonian fluid – the fluid particles are in thermodynamic equilibrium with their neighbors [3].

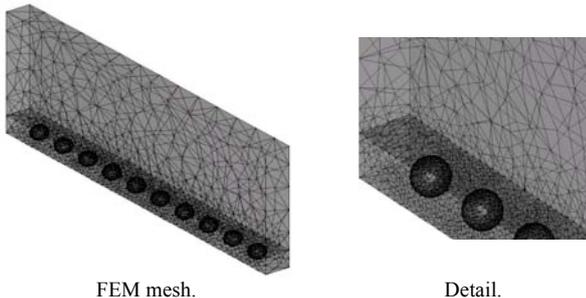
The boundary conditions in the forced convection cooling problem are defined as follows: specified (cooling air) temperature ( $T_0$ ) and velocity ( $u_y$ ), at the inlet and in the far field, above the SPVC module, no-slip conditions at the SPVC module surface, symmetry conditions on the lateral walls (computational domain – flow and SPVC module), normal flow and uniform pressure for flow and flux, convective flux boundary condition for heat transfer at the outlet.

Figure 3,a displays the SPVC module structure and the assumed boundary conditions in the forced convection heat transfer problem. The SPVC module is made of tiny spherical solar cells (1.8 mm in diameter) embedded in clear glass. The spacing between cells is not a degree of freedom, and it is imposed by technological reasons: the spheres should not shadow each other, nor should they be too loosely packed (the module has to be compact) [8].

The boundary conditions in the forced convection cooling problem are defined as follows: specified (cooling air) temperature ( $T_0$ ) and velocity ( $u_y$ ), at the inlet and in the far field, above the SPVC module, no-slip conditions at the SPVC module surface, symmetry conditions on the lateral walls (computational domain – flow and SPVC module), normal flow and uniform pressure for flow and flux, convective flux boundary condition for heat transfer at the outlet. The mathematical model for heat transfer was implemented and solved in COMSOL, which uses the finite element Galerkin formalism.



a. Computational domain and boundary conditions.



b. FEM mesh – Delauney, unstructured mesh.

**Fig. 3** The heat transfer problem.

Figure 3,b shows the FEM mesh, made of Lagrange tetrahedral elements: quadratic for temperature, and  $P_2$ - $P_1$  pressure model for flow [3]. The mesh was refined at the interface region between the air and SPVC wall, to increase the resolution where the wall boundary layer starts developing. Approximately 80,000 elements were needed to obtain grid independent solutions. The linearized algebraic systems of equations were solved with the direct UMFPACK solver. The relative tolerance was set to  $10^{-6}$ .

#### 4. Results And Discussion

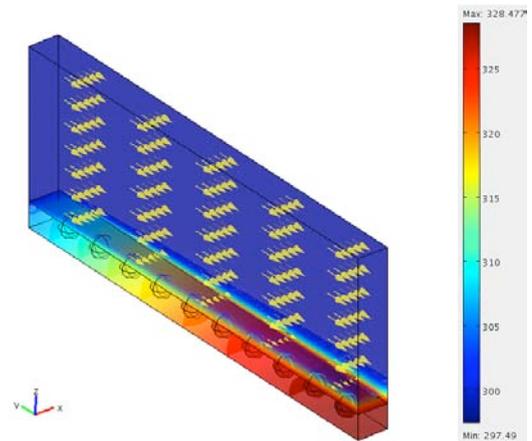
As with all photovoltaic systems, the thermal working conditions are a menace to the stability and electrical efficiency of the spherical cells. In order to optimize the thermal design of SPVC panel we investigate the influence of various environmental conditions, such as the outdoor temperature and the wind speed.

In this study we are concerned with the overall thermal

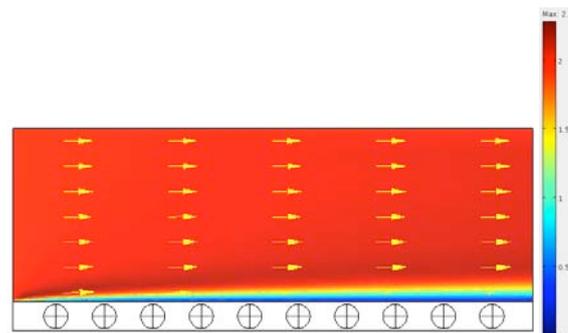
resistance between SPVC panel (with internal heat generation) and the stream of cooling air for two particular cases: natural and forced convection cooling. In what follows, we report numerical simulation results obtained by utilizing the mathematical model developed to this aim.

##### A. Forced Convection Working Conditions

Figure 4a,b depicts simulation results for the forced convection cooling – the flow (arrows) and temperature (isotherms) fields, and details of the flow structure.



a. Forced convection heat transfer ( $v_{in} = 2$  m/s).



b. The developing velocity boundary layer in forced convection flow over a SPVC panel – the cooling fluid is air.

**Fig.4** Heat transfer results – temperature and flow spectra.

The isotherm profiles unveil the complex heat transfer mechanisms, and details such as the hottest areas in the SPVC panel. Heat dissipation from the cells to the environment is apparently dominated by conduction, within the SPVC panel (the isotherms profiles are almost vertical), and by convection, within the flow field. Spherical solar cells are specifically designed to receive sunlight three-dimensionally, not only as direct sunlight but also as diffused light, and to efficiently absorb the solar radiation. So, the spherical cells generate and are exposed to significant amounts of heat, higher than the embedding structure of the panel.

The simulation results presented in figure 4,b show the convection driven flow of air from the inlet (the left margin in  $y$  direction) to the outlet (the right margin in  $y$  direction). Heat is conveyed off the panel to the ambient by the air that sweeps the panel entrained by the flow.

Figure 5 reports simulation results for various ambient conditions (wind speed in the range  $0.5 \text{ ms}^{-1} < v < 3.5 \text{ ms}^{-1}$  and inlet temperatures specific to winter and summer operation). As expected, the lower the ambient temperature ( $T_{inlet}$ ) and the higher the wind speed, the lowest the hot spot temperature in the panel.

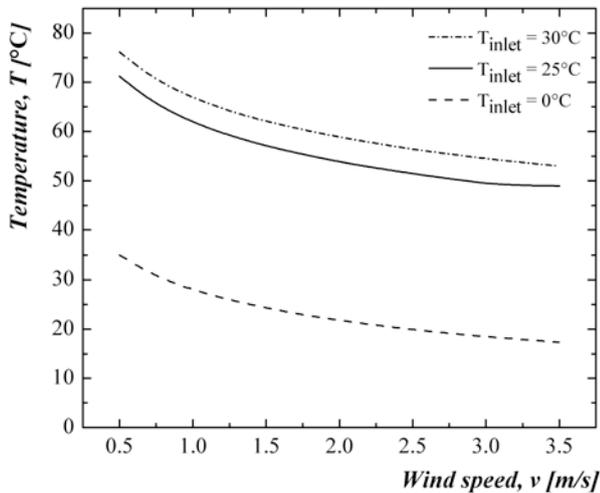


Fig.5 Forced convection – various environmental conditions.

### B. Natural Convection Working Conditions

The analysis of the coupled thermal-fluid models was performed for laminar, natural convection working conditions of a SPVC panel to obtain information on the thermal load, the high temperature regions in the panel, the heat drained out of the panel. The mathematical model consists of eqs. (1)-(4). A body force term added to the momentum equations  $T_0$  accounts for the effect of the thermal flow, (Boussinesq approximation [5]).

The boundary conditions that close the model are as follows: no-slip flow conditions at the panel wall; the inlet velocity (at the bottom edge, Fig. 6,a) is zero; normal flow/zero pressure at the top margin of the panel; the fresh air is at 25 °C; convective heat flux condition at the top margin of the panel.

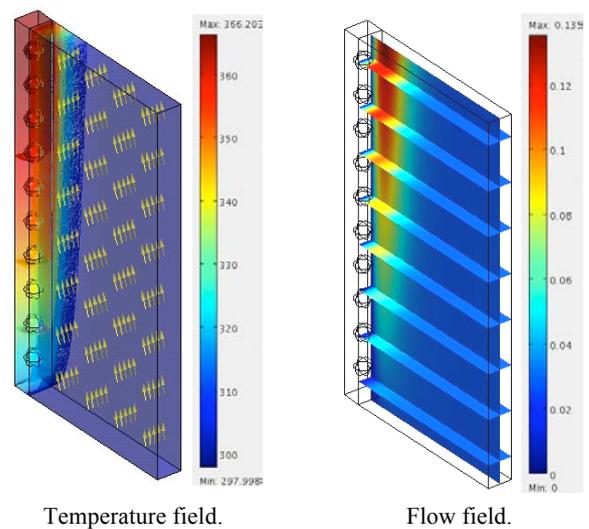
Within the panel, heat is transferred from the spherical solar cells – where it is produced by Joule effect – and from the embedding glass – that is heated by (solar) radiation – to the outer surface of the panel by conduction (Fourier law), and from the panel outer surface to the ambient by free convection. The ambient temperature is assumed 27 °C. Purely convective heat flux boundary condition is assumed on the top margin of the computational domain; the back face of the panel is thermally insulated.

In this analysis, the fluid density is a function of temperature only, therefore the local density,  $\rho$ , is temperature dependent; the fresh air density is  $\rho_0$ . These assumption results in a local buoyancy force expressed as  $(\rho-\rho_0)g$ , eq. (1). The model also treats viscosity,  $\eta$ , as temperature dependent.

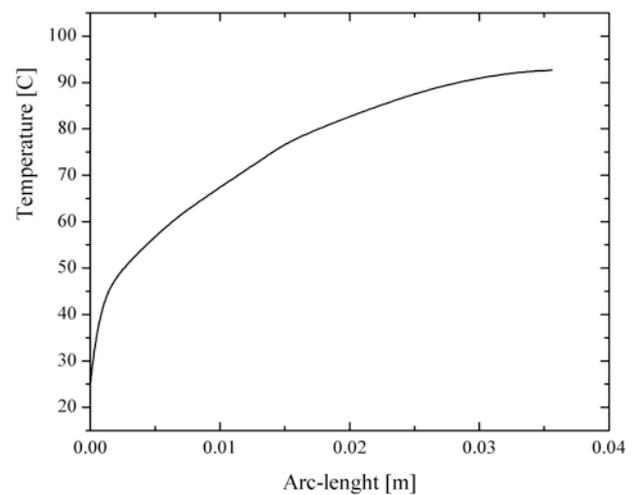
### Vertical SPVC Panel

Figure 6 depicts numerical simulation results for a vertical SPVC panel: the flow field is presented by streamlines, arrows and slices, and the temperature field is seen through isotherms. As expected, the temperature within the SPVC panel is considerably higher in natural convection cooling than in the forced convection model reported earlier.

The heat transfer mechanisms are apparent. The temperature rise along the SPV surface is explained primarily by the fluid-flow pattern. There are two regions: a thin layer adjacent to the solid surface, where the heat transfer from the SPVC panel to the main stream is a boundary layer problem; the stagnant air, outside the boundary layer, where heat is transferred by diffusion.



a. Natural convection heat transfer by a vertical SPVC panel.



b. Temperature profile along the SPVC panel surface in the direction of the flow.

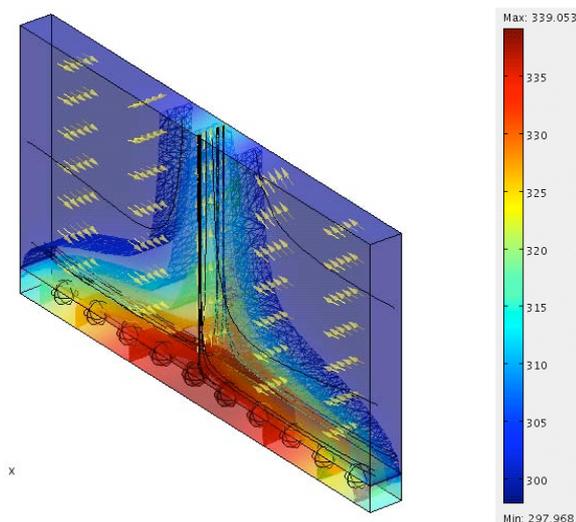
Fig.6 Heat transfer results (vertical orientation).

### Horizontal SPVC panel

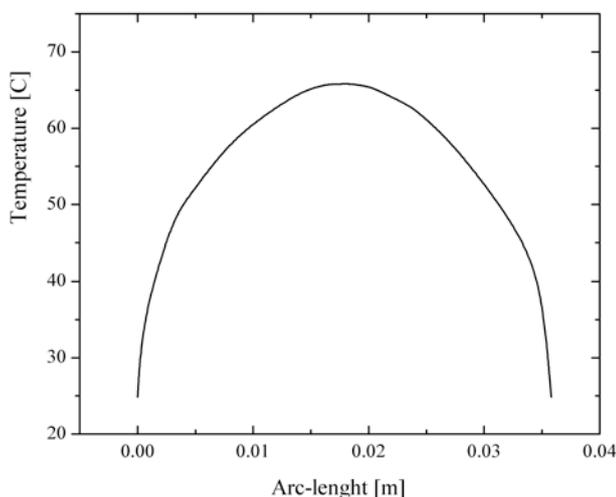
Figure 7 shows the temperature distribution (isotherm profiles) and the free convective flow pattern for a horizontal SPVC panel.

The arrows (velocity) are normalized to better outline the flow and the heat current details. Here, the boundary layer is seen to develop into a plume. However, depending on the panel size, several plumes may be produced [6].

In this analysis the heat transfer is more effective for the horizontally oriented panel. The hottest region in the SPVC panel is identified in the central area; the margins are conveniently cooled due to the streams of air that are entrained by the central, ascending plume.



a. Temperature and flow fields.



b. Temperature profile along the SPV module surface in the flow direction, along  $Oy$  axis.

Fig.7. Natural convection heat transfer (horizontal panel).

## 5. Conclusions

This paper reports a numerical analysis of the heat transfer in cooling a SPVC panel. First, a simplified 2D model is used to evaluate the resistive (Joule) heat source within the SPVC. Next, the heat transfer problem that accounts for both Joule heat source and heat received by direct illumination is solved, by utilizing 3D models.

The heat drained from the SPVC panel depends on the ambient conditions. However, forced convection may

conveniently be utilized for carrying it away.

Natural convection is also an option for cooling the SPVC panel. Here too, the ambient thermal conditions play a significant role in the heat transfer process. Another factor is the position of the panel – from vertical to horizontal. For the case under investigation, the horizontal position may provide for lower thermal loads within the panel.

Although simplified, the presented models bear the main features of the real heat transfer problem of the SPVC panels; they help investigating the panel thermal working conditions, their thermal load, and the influence of the operational layout upon the thermal load. They provide valuable information on the heat transfer paths within the SPVC module and in the surrounding environment (air), and evidences the hot spots within the structure. This study may be of interest in the design phase of SPVC modules.

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