Geometry optimization of a thermophotovoltaic system using the finite element method

V Ionescu  
Department of Physics and Electronics, Ovidius University, Constanta, 900527, Romania  
E-mail: v_ionescu@univ-ovidius.ro

Abstract. Thermophotovoltaic (TPV) systems convert heat into electricity by thermally radiating heat onto a photovoltaic (PV) diode array. They have potential applications as TPV combined heat and power (CHP) generation units, with radiators based on SiC or Yb2O3 and considering as a heat source a combustion flame. Small area PV cells can be used in order to reduce the system costs, and the use of some specials mirrors for radiation focusing onto photocells became necessary. Unfortunately, if the intensity of the radiation focused by mirrors becomes too high, the PV cells can overheat and degrade. In this paper, it was developed a basic TPV model using commercial Finite Element Method (FEM) package Comsol Multiphysics (version 5.0). The lengths of the mirrors and of the photocells were optimized by selecting a geometrical model having the optimal operating temperature low enough to ensure a reduced temperature gradient in the vicinity of the mirrors. The optimal mirror length \( l_m \) was selected from three different values of 8, 10 and 12 mm by computing the electrical output power at various emitter temperatures, surface radiosity and surface irradiation along one quarter of device circumference, 2D temperature map in a region with two adjacent mirrors and one PV cell for a constant photovoltaic cell length \( l_{pv} = 10 \) mm.

1. Introduction

A thermophotovoltaic generator system (TPV) is able to convert the radiant energy of a combustion into electrical energy, and this conversion is realized by using photovoltaic cells under the form of thermally radiating photons, which are subsequently converted into electron-hole pairs via a low-bandgap photovoltaic (PV) medium; these electron-hole pairs are then conducted to the leads to produce a current [1–3].

Modern high-temperature production processes, such as metallurgy and iron making, are usually accompanied by the generation of a large quantity of high-temperature waste heat (1000–1800 K). Bauer et al.[4] analyzed the application prospect of the TPV technology using the waste heat in the glass production and the results indicated that the large-scale use of the TPV heat recovery in the UK glass industry could provide approximately 21% of the site electricity on average and reduce energy related \( \text{CO}_2 \) emissions by approximately 6%.

In the case of a combustion flame, thermophotovoltaics can be a technology for co-generation of heat and electricity without the need of any moving parts, commonly referred to as combined heat and power (CHP) generation unit. This is a new, smarter technology developed in order to substitute in the future the classical oil-fired boilers. In general, a combustion driven TPV power system consists of a burner/thermal sources, radiant emitter and TPV cell arrays. TPV systems integrated into CHP units...
able to generate an electrical power of 1 – 1.5 KW and a thermal power varying between 12 and 20 KW could reach in the future a price of about 0.1 – 0.15 euro per kWh [5,6].

The work of T.A. Butcher et al. [7] has demonstrated the feasibility of achieving a self-powered oil-fired hydronic CHP heating system incorporating electrical power generation using TPV technology. The net power produced in a full size thermo-photovoltaic cell array using flat plate SiC emitters was about 119 W, which is the power requirement for a boiler that uses low-power auxiliary components. J. Wang et al. [8] evaluated the performance of TPV cogeneration systems with SiC or Yb₂O₃ radiator and is based PV cell arrays, using industrial high-temperature waste heat. The electrical efficiency of the system could reach 3.1% with a Yb₂O₃ radiator at an emitter temperature of 1573 K.

In order to withstand an internal TPV system temperature of 1000-1300°C, high efficiency and very expensive semiconductor cells were used, like InGaAsSb TPV cell working at a temperature of 1197°C [9]. Small area PV cells can be used in order to reduce the system costs, and the use of some specials mirrors for radiation focusing onto photocells became necessary. Unfortunately, if the intensity of the radiation focused by mirrors becomes too high, the PV cells can overheat and degrade.

The present work uses the Heat Transfer with Surface-to-Surface Radiation interface from commercial Finite Element Method (FEM) package Comsol Multiphysics (version 5.0) in order to model a TPV system based on a TPV prototype system developed by B. Bitnar [10] where a selective Yb₂O₃ emitter, heated by a butane burner illuminates high efficiency monocrystalline Si solar cells; the emitter temperature was almost 1800°C in this experimental system with a voltaic efficiency of 2.4%, and gold coated glass mirrors were included here.

The purpose of this paper is to optimize the length of the mirrors and of the photocells in terms of surface radiosity and surface irradiation by selecting a model having the optimal operating temperature low enough to ensure a reduced temperature gradient in the vicinity of the mirrors.

2. System modelling

The present TPV model uses the Heat Transfer with Surface to Surface Radiation interface. The feature Heat transfer in solids contained by this interface resolved the equation governing heat transfer through convection and conduction in terms of temperature T (considered here constant in time) for all the solid domains [11]:

\[ \rho C_p u \nabla T = \nabla (k \nabla T) + Q \]  

(1)

where \( C_p \) denotes the specific heat capacity (J/Kg·K), \( u \) is the velocity vector (m/s), \( k \) is the thermal conductivity (W/m·K), \( \rho \) is the density (Kg/m³) and \( Q \) is a source term representing the internally generated heat (W/m³).

Heat transfer in fluids feature resolved an equation similar to (1) for air domain. An absolute pressure \( p_a = 1 \) atm and an initial temperature \( T = 293.15 \) K were considered in those two heat transfer features. At outer boundary of the insulation domain the convective heat flux was defined as [12]:

\[ -n(-k \nabla T) = q_0 = h(T_{ext} - T) \]  

(2)

were \( n \) is the normal vector of the boundary and \( h \) is the heat transfer coefficient (W/m²·K).

Surface temperature of the domain was \( T_{ext} = 293.15 \) K and considering here convective air cooling, \( h = 5 \) W/m²·K.

For inner and outer boundaries of PV Cell domains it was specified the heat flux as boundary condition in the form of:

\[ -n(-k \nabla T) = Q_b \]  

(3)

In relation (3), for outer boundaries:

\[ Q_b = h_{pv} (T_{amb} - T) \]  

(4)

and for inner boundaries:
In equation (4) considering convective water cooling for cell domains, \( h_{PV} = 50 \text{ W/m}^2\text{K} \) and ambient temperature in the surrounding space of PV cells is \( T_{amb} = 273.15 \text{ K} \).

As model variables, we defined the electric power of TPV cell \( q_{out} \) using the relation:

\[
q_{out} = -G\eta_{pv}
\]

considering that PV cells converted a fraction of the irradiation to electricity instead of heat.

The other model variable, PV cell’s voltaic efficiency \( \eta_{pv} \) depends on the local temperature, with a maximum of 0.2 at 800 K:

\[
\eta_{pv} = \begin{cases} 
0.2 & T \leq 1600 \text{ K} \\
0 & T > 1600 \text{ K} 
\end{cases}
\]

For the outer boundary of insulation domain it was specified \textit{surface to ambient radiation} with the net inward radiative flux defined as [13]:

\[
-n(-k \nabla T) = \varepsilon \sigma (T_{amb}^4 - T^4)
\]

where \( \varepsilon \) is the surface emissivity and \( \sigma = 5.6703 \cdot 10^{-8} \text{ W/m}^2\text{K}^4 \) is the Stefan-Boltzmann constant.

For the inner boundaries of PV cell domains, the outer boundaries of emitter and the inner boundary of insulation domain it was specified \textit{surface to surface radiation} based on the followings:

\[
-n(-k \nabla T) = \varepsilon (G - e_b(T))
\]

\[
e_b(T) = n^4 \sigma T^4
\]

The irradiation flux \( G \text{ (W/m}^2) \) is related with radiosity flux \( J \text{ (W/m}^2) \) based on the equation [13]:

\[
(1 - \varepsilon)G = J - \varepsilon \cdot e_b(T)
\]

The geometry and dimensions of the TPV system under study are depicted in figure 1a.

![Figure 1](image-url)
The mesh discretization for the present finite-element model can have some specified degree of refinement, producing either an extremely coarse or an extremely fine mesh. This TPV model was meshed starting from a “user-controlled mesh” sequence type, calibrated for fine mesh discretization, and we selected the following element size parameters for the mirror and emitter domains: maximum element size of 1 mm, minimum element size 0.024 mm (see figure 1.b). Maximum element size for the rest of domains was 4.24 mm. Maximum element growth rates and curvature factor were selected to be 1.3 and 0.3, respectively.

The material properties used for this FEM model are summarized in table 1.

Table 1. Material physical properties.

| Component   | $k$ [W/(m·K)] | $\rho$ [kg/m³] | $C_p$ [J/(kg·K)] | $\varepsilon$ |
|-------------|----------------|-----------------|-------------------|--------------|
| Emitter     | 10             | 2000            | 900               | 0.99         |
| Mirror      | 10             | 5000            | 840               | 0.01         |
| PV Cell     | 93             | 2000            | 840               | 0.99         |
| Insulation  | 0.05           | 700             | 100               | 0.1          |

3. Results and discussions

In order to investigate the optimal operating temperature of the system at which attains the maximum electrical output, a parametric solver was used in Comsol Multiphysics. The stationary solution for a range of emitter temperatures between 1000 K and 2000 K was computed for the TPV models having a constant value of $l_{PV} = 10$ mm at three different values for $l_m$ (8, 10 and 12 mm), as we could see from figure 2. Here we could observe that the maximum value of electric power slightly moves to a lower emitter temperature as the mirror length decreases, translating from 1700 K at $l_m=12$ mm to 1600 K at $l_m=8$ mm.

A closer view of temperature distribution in the vicinity of a PV cell is presented in figure 3 for the same TPV system models. From here we could conclude that the highest temperature distribution between two adjacent mirrors and a PV cell is attained for the model with $l_m = 12$ mm, with temperature gradients of about 1450 -1460 K at the mirror regions and 1300 K at PV surface domain. No major difference could be established regarding the temperature distribution in the case of the models with $l_m = 8$ mm and $l_m = 10$ mm.
Figure 3. Temperature distribution in the PV system models at their optimal temperatures of the emitter (at \( l_{PV} = 10 \text{ mm} \)).

Surface radiosity, which represents all radiant energy leaving a surface, was plotted in figure 4 along a quarter of the cell circumference for the three TPV system models with \( l_{PV} = 10 \text{ mm} \). From this representation we could see that the system model having \( l_m = 10 \text{ mm} \) presented the most symmetrical distribution of surface radiosity between two adjacent mirrors - PV cell pairs. Corroborating this result with observations made from figure 2 and figure 3, we decided to use the dimension \( l_m = 10 \text{ mm} \) as an optimal value of mirrors length in the present system modelling.

Figure 4. Surface radiosity along the TPV cell model for one quarter of the device circumference at \( l_{PV} = 10 \text{ mm} \).

Next, the length of the PV cells was varied at values between 9 mm and 11 mm, with an increment of 0.5 mm and a model simulation was performed again in order to study the mutual surface irradiation in the TPV cell along a quarter of his circumference (see figure 5). From the plot we could observe that radiative flux varies significantly between the inner surface of insulation part and mirrors as an effect of shadowing. The most uniform distribution of surface irradiation along the two PV cells located in one quarter of the system was observed in the system model with \( l_{PV} = 9.5 \text{ mm} \) (see the clear delimitation of the constant irradiation at a value of 220 kW/m\(^2\) in the regions situated between 110 – 120° and 155-165° along the cell circumference).
Figure 5. Surface irradiation distribution for one quarter of the cell circumference at \( l_m = 10 \) mm.

4. Conclusions

The maximum point of electrical output power in the PV system was displaced to a lower emitter temperature of 1600 K with the decreasing of mirror length \( l_m \) from 12 mm to 8 mm.

The TPV model having \( l_m = 12 \) mm presented the highest temperature gradient and the most symmetrical distribution of surface radiosity between two adjacent mirrors and a PV cell.

The TPV model with \( l_m = 12 \) mm and PV cell length \( l_{PV} = 9.5 \) mm showed the most uniform distribution of surface irradiation along the two PV cells located in one quarter of the system. Finite Element Method modelling can reduce significantly the development time for practical implementation of TPV systems by optimizing the mirror and TPV cell geometry, depending on the best operating conditions.

5. References

[1] Black R E, Baldasaro P F and Charache G W 1999 18th International Conference on Thermoelectrics (Baltimore, MD, USA, 29 August- 2 September 1999) pp 639-644
[2] O’Sullivan F, Celanovic I, Jovanovic N, Kassakian J, Akiyama S and K. Wada 2005 J. Appl. Phys. 97 033529
[3] Xue H, Yang W, Chou S, Shu C and Li Z 2005 Nanoscale Microscale Thermophys. Eng. 9 85.
[4] Bauer T, Forbes I and Pearsall N 2004 International Journal of Ambient Energy 25 19
[5] Palfinger G, Bitnar B, Durish W, Mayor J C, Grutzmacher D and Gobrecht J 2003 Semiconductor Science and Technology 18 254
[6] Fraas L M, Avery J E, Huang H X 2003 Semiconductor Science and Technology 18 247
[7] Butcher T A, Hammonds J S, Horne E, Kamath B, Carpenter J and Woods D R 2011 Applied Energy 88 154.
[8] Wang J, Ye H, Wu X, Wang H and Xu X 2013 Front. Energy 7 146
[9] Kin K, Douglas M, Hayden A C S 2009 Energy Conversion Engineering Conference (Denver, Colorado, 2-5 August 2009) pp 1-9
[10] Bitnar B 2003 Semiconductor Science and Technology 18 221
[11] Knoerzer K, Juliano P, Roupas P and Versteeg C 2011 Innovative Food Processing Technologies: Advances in Multiphysics Simulation (UK: John Wiley & Sons)
[12] T. Defraye T, B. Blocken B and Carmeliet J 2010 International Journal of Heat and Mass Transfer 53 297
[13] Cengel Y A and Ghajar A J 2015 Heat and Mass Transfer: Fundamentals and Applications 5th Ed. (New York: Mc. Graw-Hill Education)