Modeling Integrated Thermoelectric Generator-Photovoltaic Thermal (TEG-PVT) System

R. Kiflemariam*[1], M. Almas[1], and C. Lin[1]

[1]Department of Mechanical and Materials Engineering
Florida International University, Miami, FL
*Email: rkifl001@fiu.edu

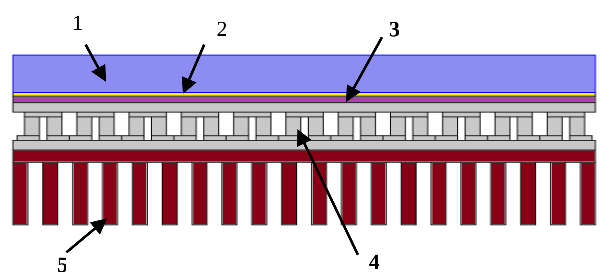
Abstract: A 2D steady state heat conduction-electric current model was created in COMSOL Multiphysics to study the performance of thermoelectric generator-photovoltaic-thermal (TEG-PVT) system. Four different cases were studied in the paper. In case 1, PV cells without concentrator was simulated while in case 2, concentrator ratio range from 2 to 5 was utilized In case 3, the convection heat transfer coefficient was varied between 6.2 and 14.2 W/m^{2}K. The value of thermal insulation between PV cells and TEG was decreased for case 4. The results indicate that having higher concentration ration results in more power generation while increases convection heat transfer coefficient between outside surfaces and atmosphere and lower thermal resistance between PV cells and TEG help keep the PV temperature at optimum level.

Keywords: Thermoelectric generator, Photovoltaic thermal (PVT), air cooling, COMSOL

1. Introduction

There is a demand for efficient and clean energy due to the rising cost of energy and globally increasing environmental awareness. Thermoelectric generation is a promising technology which cleanly converts waste heat into electricity. They have been applied in aerospace applications and waste heat recovery from cars and industries [1-3]. Photovoltaic (PV) based technology is also another clean source of energy which produces electricity from sunlight. However, the efficiency of PV decreases with PV cell temperature and they need to be cooled to maintain their efficiency by removing waste heat from the panels. The waste heat from the PV panels could be put into useful energy by using TEG. Thus, there has been researches on integrating photovoltaic cells and thermoelectric system into one hybrid generation system [4-8]. One of the problems cited in the studies was the low temperature across the TEG which minimizes the power generated by TEGs. Therefore, the performance of a hybrid Photovoltaic thermal-thermoelectric generation with finned air cooling has been studied numerically using COMSOL and the results are presented.

The basic design consists of TEG modules attached to the base of PV modules as shown in Figure 1. The cold side of the TEG module is also connected to finned heat sink. The heat sink helps cool both the PV and the TEG. The arrangement is depicted in Fig. 1. Four different cases were studied. In the first case (case 1), PV cell with no concentrator is simulated. In the second case (case 2) the concentration ratio and heat transfer coefficient between was varied between 2 to 5. For the third case (case 3), convection heat transfer coefficient between the PV cells and atmosphere and at cold heat sink attached to the TEG module is varied between 6.2 and 14.2 . In the fourth case (case 4), the thermal insulation conductivity was changed.



1	Glass Cover
2	PV cells
3	Insulator
4	TEG module
5	Finned heat sink

Figure 1. Schematic of PVT-TEG system

2. Governing equations

The heat absorbed by the PV panels is given by:

$$\dot{Q}_{net} = \dot{Q}_{abs} - \dot{Q}_{rad,r} - \dot{Q}_{conv} \quad (1)$$

where Q_{abs} is the product of incident insolation on the PV surface (G), the concentration ratio (C_r), efficiency of PV (η_{pv}) and area of the PV (A_P).It is represented in the computational model as a heat source in PV domain.

$$\dot{Q}_{abs} = (1-\eta_{PV})C_r G A_P \quad (2)$$

$\dot{Q}_{rad,r}$ is the heat reflected back to the surrounding air and is described as:

$$\dot{Q}_{rad,r} = \varepsilon\sigma(T_{PV}^4 - T_{amb}^4)A_p \quad (3)$$

where ε is the emissivity of the PV surface, σ is the Stefan-Boltzmann constant and T_{Pv} and T_{amb} are the temperatures of PV panel and the surrounding air respectively. It is represented as surface boundary condition 1 (BC1 in Fig. 2).

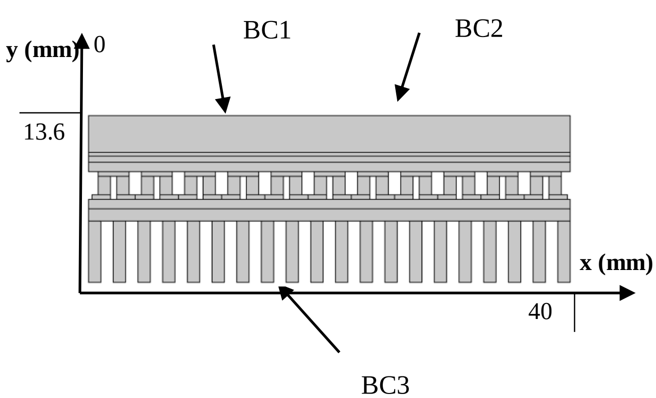


Figure 2. Computational model of integrated system

$\dot{Q}_{conv}$ represents the convection heat loss to the surrounding atmosphere and is depicted as surface boundary condition 2 and 3 which are BC2 in the PV surface and BC3 on the surfaces of fins respectively.

$$\dot{Q}_{conv} = h(T_{PV} - T_{amb})A_P \quad (4)$$

where h is the convection heat transfer coefficient

A TEG module generates electric potential (V_{sb}) when a temperature difference is maintained between the hot and cold sides of the TEG, and its magnitude is proportional to the difference in Seebeck coefficient (α) of the two pairs of TEG elements. The pairs of the TEG elements are designated as *p* and *n* elements. The power generated from TEG module can be expressed as Eq.5:

$$P_{gen} = V_{sb}R_{eq} = [\frac{2n_{pn}(\alpha_p - \alpha_n)(T_{hs} - T_{cs})}{R_{e,p} + R_{e,m}}]^2 R_{e,p} \quad (5)$$

where T_{hs} and T_{cs} are the cold and hot side temperature of the TEG module, α_P and α_N are the Seebeck coefficients of the *p* and *n* elements, respectively. n_{pn} is the number of *p* and *n* elements in a TEG module. R_{eq}, $R_{ep,}$ and $R_{e,\ m}$ are the equivalent total electrical resistance, external electric resistance and the internal TEG module electric resistance respectively.

The heat flow in the TEG as described in Eq. 6 is mainly due to the temperature difference between the hot side and cold side of the thermoelectric generator but the heat flow due to peltier effect (the first term on the left hand side of Eq. 6) and joule heating (the last term in Eq.6) also contribute to the total heat flow in the TEG. The total heat flow in the TEG module is given as:

$$\dot{Q}_{\text{mod}} = 2NI\Delta T_{PN}(\alpha_p - \alpha_N) - K(T_{hs} - T_{cs}) - \frac{I^2 R}{2} \quad (6)$$

Table 1. Thermal properties

Name	Value
Seebeck coefficient_Bi2Te3	205e-6[V/K]
electric conductivity_Bi2Te3	1.1e5[S/m]
thermal conductivity_Bi2Te3	1.6[W/(m*K)]
specific heat capacity_Bi2Te3	154.4[J/(kg*K)]
density_Bi2Te3	7740[kg/m^3]
thermal conductivity copper	400[W/(m*K)]
electric conductivity cu	5.998e7[S/m]
thermal conductivity_PV	139[W/(m*K)]
thermal conductivity glass	1.1[W/(m*K)]
thermal conductivity insulation	0.035[W/(m*K)]

Table 2. Geometrical Properties

Name	Value
pellet width	1[mm]
pellet height	1.5[mm]
electrode thickness	0.38[mm]
gap between pellets	1.4[mm]
height ceramic	0.9[mm]
fin base height	1[mm]
fin base width	40[mm]
fin height	5[mm]
fin width	1[mm]
gap between fins	5[mm]
number of fins	20
height PV	0.3[mm]
width PV	40[mm]
height glass cover	3[mm]
width glass cover	40[mm]
height back insulation	0.5[mm]
width back insulation	40[mm]

3. Use of COMSOL Multiphysics

A 2D model of thermoelectric generator, heat source PV panel and the microchannel heat sink is constructed and numerical simulations were conducted using the FEM solver COMSOL (Version 4.4).

The heat transfer module (ht) is used to study heat transfer and fluid flow parameters and results of temperature, velocity, and pressure field are obtained. The electric current module (ec) is also used to estimate electric potential and power generation from TEG module. The modules are linked using weak form equation which represents the seebeck effect.

The simulation parameters are concentration ratio is varied from C=2 to C=5 and the convection heat transfer which is defined corresponding to the wind velocity U=1 m/s to 3 m/s. The ambient temperature is kept at 298 K.

Mesh grid independence study were carried out and fine mesh with 5314 elements were used. Segregated group solvers were used for solving Electric potential (V), Temperature field (T), Velocity field (U), and pressure. Steady state simulations were carried out with convergence criteria of 10^{-4}.

4. Results

The power produced by TEG modules depends on the temperature difference between the hot side and cold side of the module (ΔT_{teg}). Thus, an increase in net het input in PV cells results in higher hot side temperature at the TEG module.

Case 1 refers to PV cells without concentrator (C_r=1). Simulation results indicate T_{PV}=314 K and ΔT_{teg}=1.5 K. This suggests that for a viable power production, an increase sin concentration ratio is necessary to achieve more favorable ΔT_{teg} and thus more power.

For Case 2, C_r is varied between 2 and 5. As Fig 3 shows, with an increase in concentration ratio, T_{PV} increased from 330 K to 377 K as C_r is raised from 2 to 5. With high concentration ration, more irradiation is absorbed at the surface which increases the temperature of the PV cells.

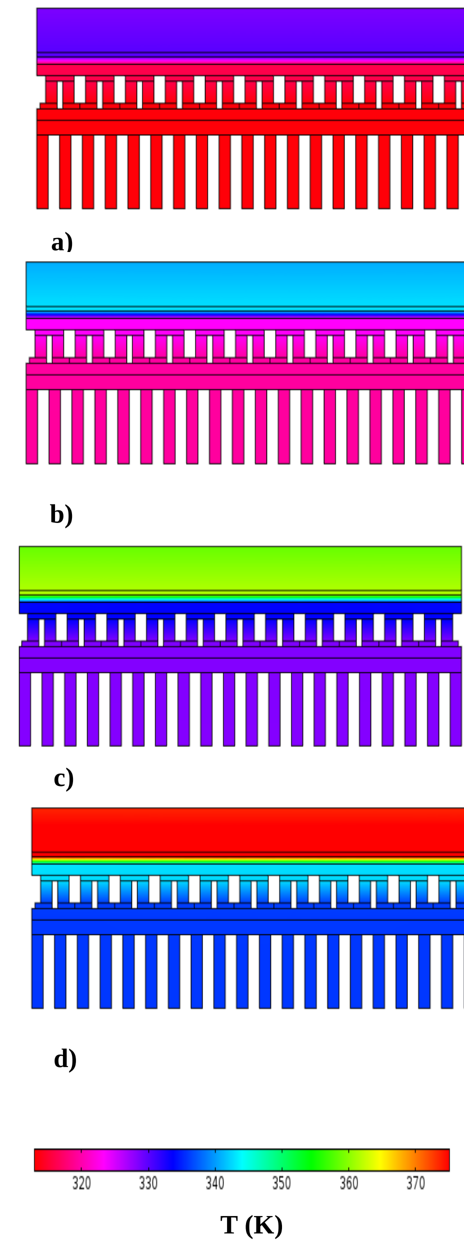


Figure 3. Temperature distribution for C equal to a) 2 b) 3 c) 4 d) 5 and h=10.4 W/m^{2}K

Likewise, the hot side temperature of the TEG module also increased by 26.5 K for a 2.5 fold increase in C_r. For a constant ambient temperature at 298 K and convection heat transfer coefficient of 10.4 W/m^2.K, ΔT_{teg} increases from 3 K to about 7.3 K.

For case 3 and as shown in Fig 4 , the effect of the cold heat sink convection heat transfer was simulated for heat transfer coefficient between 6.6 and 14.2 W/m^2.K For the constant C_r=3, ΔT_{teg} remained at the same value, but the temperature of PV cells (T_{PV}) decreased by around 18 K. Therefore, having high heat transfer at the cold heat sink helps decrease T_{PV} without affecting power production from TEG modules. The electric potential was simulated to be around 0.4 V per module (Fig 5). As there is a thermal and electrical insulation between the PV cells and TEG modules, it could be inferred that there is high T_{PV} but the hot side temperature could be less by as much as 30 K due to the thermal insulation.

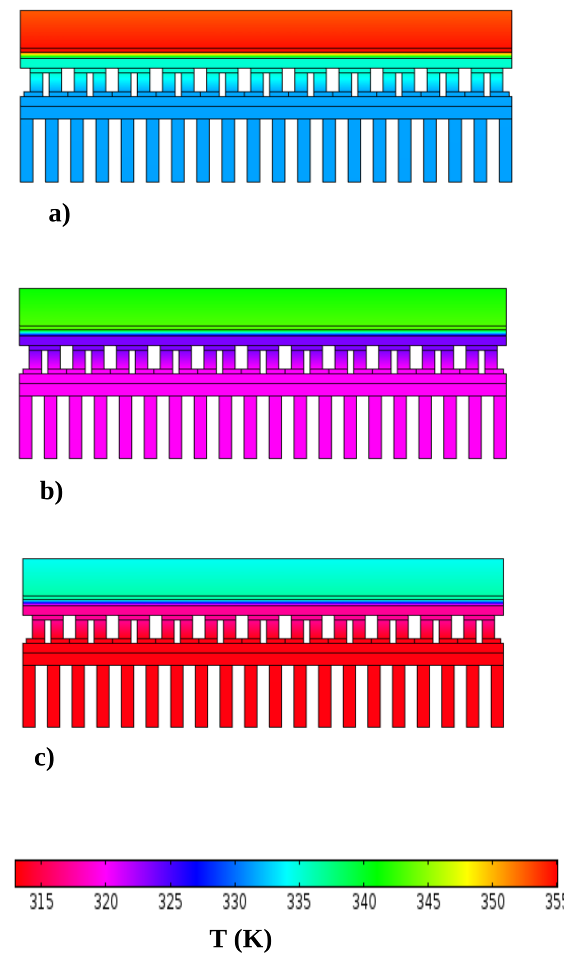
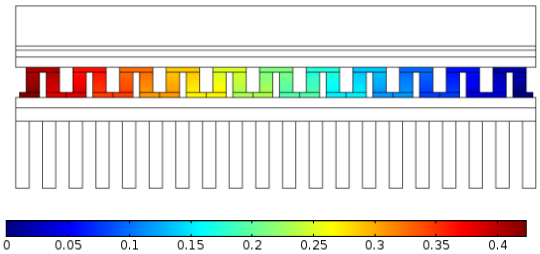


Figure 4. Temperature distribution for C=3 and wind velocity (U) of a) 1m/s b) 2m/s c) 3 m/s



Electric Potential [V]

Figure 5. Electric potential for C=3 and U=3 m/s

For case 4 the thermal conductivity of the insulation material between the PV cells and TEG module was increased. This resulted in a decrease in T_{PV} from 342 K to 328 K for C_r=3 and h=10.2 W/m^2. K which suggest that reducing thermal resistance between PV cells and TEG module could help keep PV cells t optimum temperature for higher C_r.

5. Conclusions

In this paper, the integrated design of thermoelectric generator and PVT cells is studied using COMSOL. Temperature and electric distribution in the integrated system and electric potential and current at TEG module has been simulated. The results indicate that having a higher concentration ratio results in higher power production from TEG module due to increased absorbed heat flux. It is also observed that decreasing thermal resistance between the PV cells and TEG module also assists in keeping the PV cells temperature at optimum value. With an increased efficiency of TEG modules, the integrated system could produce useful power from the TEG module augmenting power production from PV cells.

References

[1] Wang, Y., Dai, C., Wang, S. Theoretical analysis of a thermoelectric generator using exhaust gas of vehicles as heat source, *Appl. Energy*. **112**. 1171–1180(2013).

[2] Gou, X. Xiao, H., Yang, S., Modeling, experimental study and optimization on low-temperature waste heat thermoelectric generator system, *Appl. Energy*. **87**, 3131–3136(2010).

[3] Kiflemariam, R., Lin, C.X., Moosavi, R., Numerical simulation, parametric study and optimization of thermoelectric generators for self-cooling of devices, in: 11th AIAA/ASME Joint Thermophysics and Heat Transfer Conference, American Institute of Aeronautics and Astronautics, 2014.

[4] He, W. Su, Y., Riffat, S.B. Hou, J., and Ji, J. Parametrical analysis of the design and performance of a solar heat pipe thermoelectric generator unit, *Appl. Energy*. **88,** 5083–5089(2011).

[5] Muhtaroglu, A., Yokochi, A., Jouanne, A., Integration of thermoelectrics and photovoltaics as auxiliary power sources in mobile computing applications, *J. Power Sources*. **177**, 239–246(2008).

[6] Deng, Y., Zhu, W., Wang, Y., Shi, Y., Enhanced performance of solar-driven photovoltaic–thermoelectric hybrid system in an integrated design, *Sol. Energy*. **88,** 182–191(2013).

[7] Zhang, M., Miao, L., Kang, Y.P., Tanemura, S., Fisher, C.A.J., Xu, G. et al., Efficient, low-cost solar thermoelectric cogenerators comprising evacuated tubular solar collectors and thermoelectric modules, *Appl. Energy*. **109,** 51–59(2013).

[8] Xi, H., Luo, L., Fraisse, G. Development and applications of solar-based thermoelectric technologies, *Renew. Sustain. Energy Rev*. **11,** 923–936(2007).