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Design of A Thermophotovoltaic System Optimized Surface Radiative And Conductive heat flux

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Abstract— TPV systems, unlike typical electronic systems, are expected to maximize radiation heat transfer to improve efficiency. However, inherent radiation losses occur as radiation not converted to electric power contributes to the increased temperature if the PV cells. Further, heat transfer through conduction results in increased cell temperature. PV cells have a limited operating temperature range that depends on the type of material used. Solar cells are limited to temperatures below 80 °C, whereas high-efficiency semiconductor materials can withstand temperatures as large as 1000 °C. Photovoltaic efficiency is often a function of temperature with a maximum at a temperature greater than ambient. The model presented in this research aims to investigate the influence of operating conditions (flame temperature) on system efficiency and temperature of components in a typical TPV system using the Heat Transfer with Surface-to-Surface Radiation interface. The model can also assess the influence of geometry on TPV system performance.

Key Words— PV Cell, Semiconductor Materials, Solar System, compact TPV Cell

Introduction

To improve system efficiency, engineers prefer to use high-efficiency PV cells, which however can be quite expensive. To reduce system costs, engineers work with smaller-area PV cells and then use mirrors to focus the radiation on them. However, there is a limit to how much you can focus the beams; if the radiation intensity becomes too high, the cells can overheat. Thus engineers must optimize system geometry and operating conditions to achieve optimum performance at minimum material cost.

. Advancements in photovoltaic, thermal emission and compact liquid fueled combustion sources enable thermo-photovoltaic energy conversion to compete with battery and fuel technology for compact power applications. The present work identifies all components of the thermal-to-electric energy conversion (TEC) system including the balance-of-plant presenting an in-depth review of the state of the art. Evaluation of each component's performance showed that a 10% efficient thermo-photovoltaic power source could be realizable by integrating state-of-the art components. Reduction of the photovoltaic cell bandgap and Auger recombination, combined with emitters using photonic crystals to tailor the emission spectrum and heat recuperation within a combustion-based heat source, can lead to TEC efficiencies greater than 20% with temperatures below 1000 °C. Such a power source could have an energy density reaching 1000 W*h/kg and power densities in the range of 10's W/kg with a multi-fuel capability offering a tremendous advancement from today's battery technology.

Compact power sources having high energy and power densities are critical for numerous commercial and military applications. These applications can span from personal power sources for expeditions requiring long periods of time away from a power grid to unmanned air vehicles (UAVs) requiring only a few hours of running time. A power technology gap currently exists in the range of 10–100 W+ that is only spanned by battery technology because improvements in rechargeable batteries have not kept up with the power demand of new personal devices. High energy dense technologies are very much sought after to augment batteries performance and extend the available energy density range well beyond the state-of-the-art battery technology (140 W*h/kg for rechargeable lithium [Li]-ion technology [1].

There is a focus in the military to develop power technologies that capitalize on the large energy content offered by hydrocarbons or alcohols. Modest conversion efficiencies of only a few percent can provide comparable energy density to battery technology with the added capability of instant recharge. Fuel cells have seen a lot of focus at all power levels and have become a promising technology to span the power technology gap. For example, Los Alamos National Laboratories developed a direct methanol fuel cell (DMFC) useful for personal power applications, which demonstrated an energy density of 550 W*h/kg for a 72-h mission duration and delivering 20 W of average electrical power with an overall efficiency of 33% [2]. Smart Fuel Cell offers a 250-W DMFC suitable, for example, in UAV applications having approximately 464 W*h/kg (31.1 kWh in fuel cartridge and a 67-kg system weight with fuel) [3]. Smart Fuel cell also offers Energy for You (EFOY) DMFCs on their Web site, claiming 721 W*h/kg for a 40-W average electrical power using their M10 cartridge [4]. Although fuel cells continue to be improved and can have higher energy densities than batteries, there is a lack of fuel flexibility. For some applications, a mainstream fuel source such as propane, butane, gasoline, or diesel may be better options than hydrogen sources or methanol cartridges. Hydrogen fuels require engineered storage of hydrogen as a liquid or operate through the chemical release from hydrates, which currently prevent their use. Meanwhile, methanol has lower energy content than the longer chain alcohols and hydrocarbons.

Conversion of the chemical energy content of a fuel to electrical energy can be both efficient and fuel flexible by first converting the energy into heat. Electrical power converted from heat using a large temperature difference can efficiently extract the energy content and follows the Carnot efficiency. Such energy conversion has been accomplished through mechanical engines that convert chemical to mechanical through combustion and then mechanical to electrical using, for example, magnetic generators. Although mechanical heat engines are the mainstay at the large scale, there are significant challenges that exist when scaling engines below the kW level due to the increasing frictional losses and thermal management issues (*6*–*8*). Direct thermal-to-electrical conversion (TEC) is another approach to achieve high efficiencies for compact platforms that has no moving parts within the core converter. Without moving components, the converter does not have scaling issues related to contact mechanics. Additionally, TEC can use external combustion as a heat source and thus can be more flexible than internal combustion engines, especially in the choice of fuel.

This work uses Heat Transfer with Surface-to-Surface Radiation interface, investigates the influence of operating conditions (flame temperature) on system efficiency and the temperature of components in a typical TPV system. The model can also assess the influence of geometry changes.

Design and Results Discussions

The efficiency of a TPV device ranges from 1% to 20%. In some cases, TPVs are used in heat generators to co-generate electricity, and the efficiency is not so critical. In other cases TPVs are used as electric power sources, for example in automobiles [2]. In such cases efficiency is the major concern.

TPV systems, unlike typical electronic systems, must maximize radiation heat transfer to improve efficiency. However, inherent radiation losses—radiation not converted to electric power—contributes to the PV cells' increased temperature. Further, heat transfer through conduction results in increased cell temperature. PV cells have a limited operating temperature range that depends on the type of material used. Solar cells are limited to temperatures below 80 °C, whereas high-efficiency semiconductor materials can withstand as much as 1000 °C. Photovoltaic efficiency is often a function of temperature with a maximum at some temperature above ambient.

To improve system efficiency, engineers prefer to use high-efficiency PV cells, which however can be quite expensive. To reduce system costs, engineers work with smaller-area PV cells and then use mirrors to focus the radiation on them. However, there is a limit for how much you can focus the beams; if the radiation intensity becomes too high, the cells can overheat. Thus engineers must optimize system geometry and operating conditions to achieve maximum performance at minimum material costs.

The following model, which uses the Heat Transfer with Surface-to-Surface Radiation interface, investigates the influence of operating conditions on system efficiency and the temperature of components in a typical TPV system. The model can also assess the influence of geometry changes.

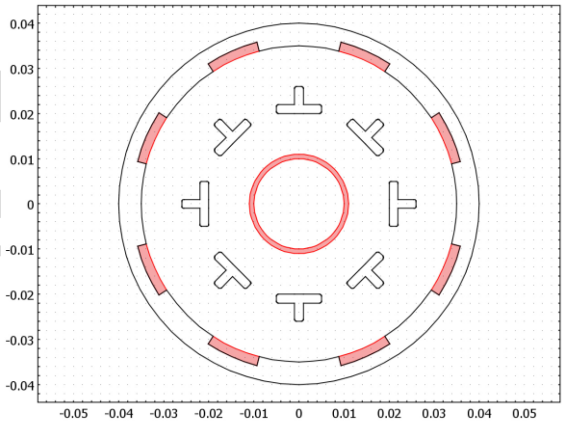


Fig.1: Geometry and dimensions of the modeled TPV system.

Fig. 1 depicts the geometry and dimensions of the system under study. To reduce the temperature, the PV cells are water cooled on their back side (at the interface with the insulation).

The following equation describes the heat fluxes, radiative flux, and conductive flux, after it comes the boundary condition equation

$$\rho C_p \frac{\partial T}{\partial t} + \nabla(-k\nabla T) = Q$$

$$-\mathbf{n} \cdot (-k\nabla T) = h(T_{\text{inf}} - T) + (\varepsilon/(1-\varepsilon))(J_0 - \sigma T^4) + q$$

Where ρ is the density, *k* denotes the thermal conductivity (W/(m·K)), *Q* represents the volume heat source (W/m^3), **n** is the surface normal vector, *h* is the convective heat transfer film coefficient (W/(m^2·K)), T_{inf} equals the temperature of the convection coolant, ε equals the surface emissivity, J_0 is the surface radiosity expression (W/m^2), and σ equals the Stefan-Boltzmann constant.

Conduction is always present on the boundaries. The model simulates the emitter with a specific temperature, T_{heater}, on the inner boundary. At the outer emitter boundary, it takes radiation (surface-to-surface) into account in the boundary condition. It simulates the mirrors by taking radiation into account on all boundaries and applying a low emissivity. The inner boundaries of the PV cells and of the insulation also make use of radiation boundary conditions. However, the PV cells have a high emissivity and the insulation a low emissivity. Further, the PV cells convert a fraction of the irradiation to electricity instead of heat. Heat sinks on their inner boundaries simulate this effect according to

$$q = -G\eta_{\mathrm{pv}}$$

Where *G* is the irradiation flux (W/m^2) and η_{pv} is the PV cell's voltaic efficiency. The latter depends on the local temperature, with a maximum of 0.2 at 800 K;

$$\eta_{\mathrm{pv}} = \begin{cases} 0.2\left[1-\left(\dfrac{T}{800\ \mathrm{K}}-1\right)^2\right] & T \le 1600\ \mathrm{K} \\ 0 & T > 1600\ \mathrm{K} \end{cases}$$

Fig. 2 illustrates this expression for temperatures above 1000 K.

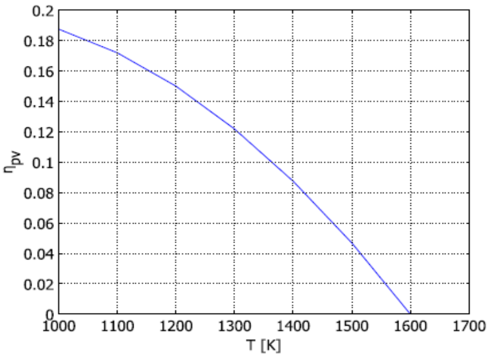


Fig. 2: PV cell voltaic efficiency versus temperature.

At the outer boundary of the PV cells, the model applies convective water cooling by setting *h* to 50 W/ (m^2·K), and T_{amb} to 273 K. Finally, at the outer boundary of the insulation it applies convective cooling with *h* set to 5 W/ (m^2·K) and T_{amb} to 293 K.

Table 1 summarizes the material properties.
TABLE 1: MATERIAL PROPERTIES

COMPONENT	***k* [/(m]·K)**	**ρ [kg/m3]**	***Cp* [J/(kg·K)]**	**ε**
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

The model calculates the stationary solution for a range of emitter temperatures (1000 K to 2000 K) using the parametric solver.

The results show that the device experiences a significant temperature distribution that varies with operating conditions. Fig.3 depicts the stationary distribution at operating conditions with an emitter temperature of 2000 K.

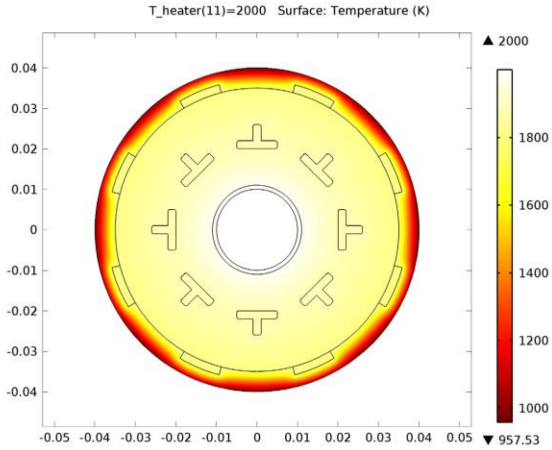
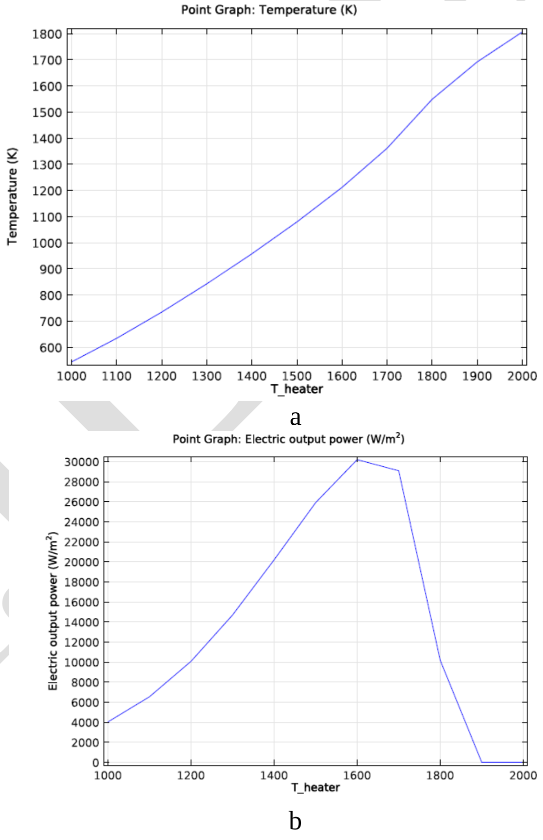


Fig. 3: Temperature distribution in the TPV system when the emitter temperature is 2000 K.

The plot in Fig. 4 (a) shows, the PV cells reach a temperature of approximately 1800 K. This is significantly higher than their maximum operating temperature of 1600 K, above which their photovoltaic efficiency is zero (see Fig. 4.3).

It is interesting to investigate what the optimal operating temperature is. The lower plot in Fig. 4.5 investigates at what temperature the system achieves the maximum electric power output. The optimal emitter temperature for this configuration seems to be between 1600 K and 1700 K, where the electric power (irradiation multiplied by voltaic efficiency) is maximum.



a

b

Fig. 4: PV cell temperature (a) and electric output power (b) versus operating temperature.

The next step is to look at the temperature distribution at the optimal operating conditions (Fig. 4.6).

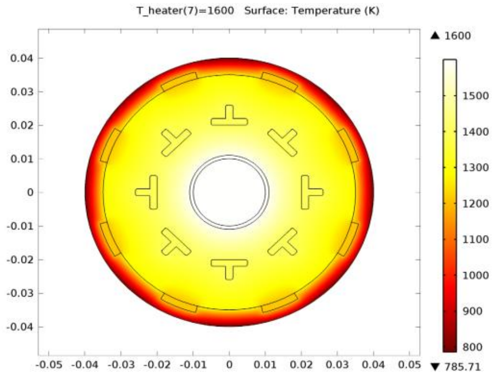


Fig. 5: Temperature distribution and surface irradiation flux in the system at an operating emitter temperature of 1600 K.

When the emitter is at 1600 K, the PV cells reach a temperature of approximately 1200 K, which they can withstand without any problems. Note that the insulation reaches a temperature of approximately 800 K on the outside, suggesting that the system transfers a significant amount of heat to the surrounding air.

IV. CONCLUSION

TPV systems have been designed and analyzed; unlike typical electronic systems, TPV systems are designed to maximize radiation heat transfer and to improve energy efficiency. However, inherent radiation losses—radiation not converted to electric power—contributes to the PV cells' increased temperature. Further, heat transfer through conduction results in increased cell temperature. PV cells have a limited operating temperature range that depends on the type of material used. Solar cells are limited to temperatures below 80 °C, whereas high-efficiency semiconductor materials can withstand as much as 1000 °C. Photovoltaic efficiency is often a function of temperature with a maximum at some temperature above ambient.

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