Mechanical Engineering Department | ME146&246, Fall 2018
UC Berkeley | Prof. V. Carey

Project 2. Solar Hybrid Power **Due date: Thursday October 25, 2018**

You may team up with a partner for this project. Do not share information or results with other groups.

General Information

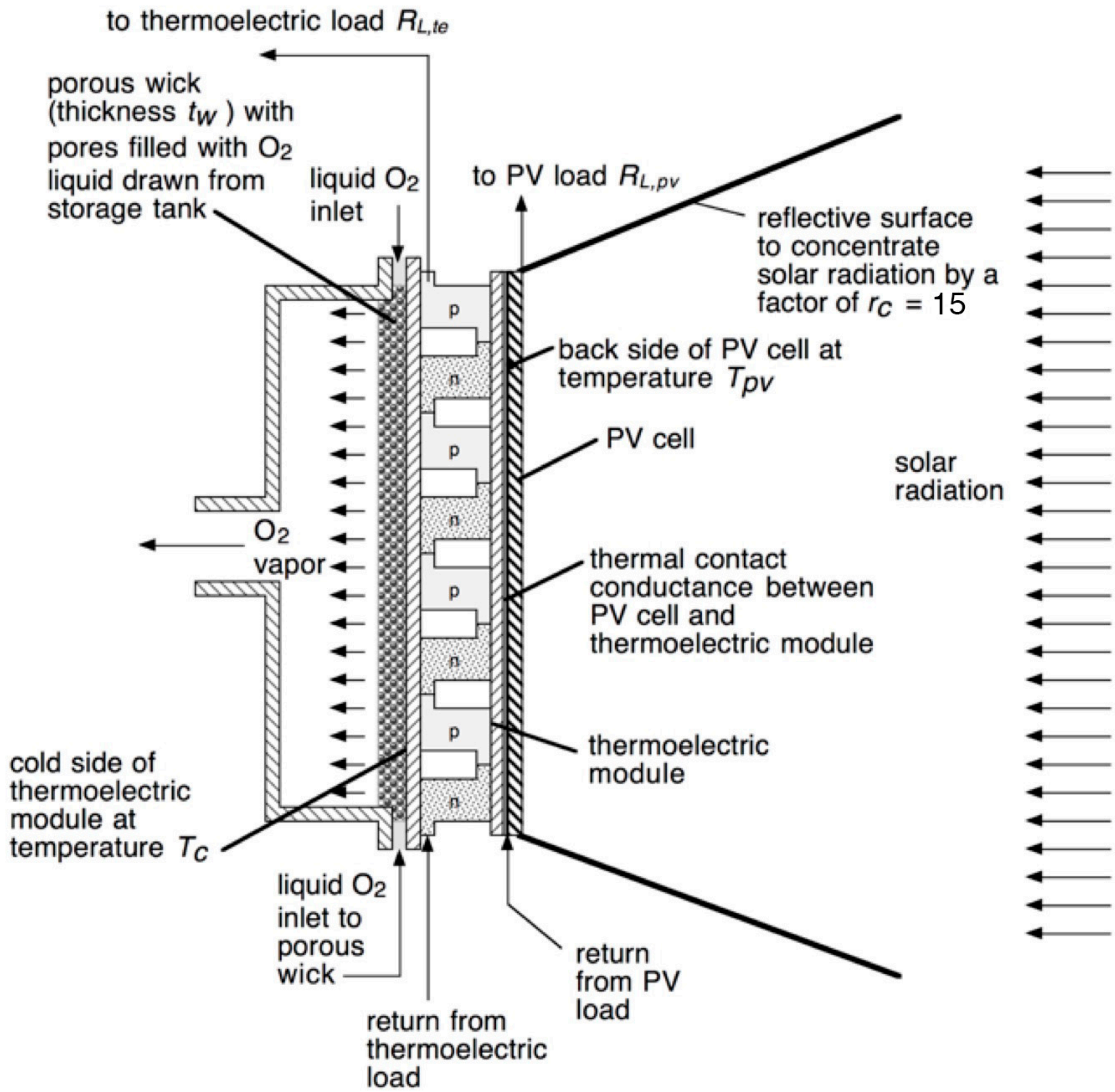


Figure 1. Schematic of the hybrid power generation system. The area of the PV cell and thermoelectric module is A_{pv}.

In this project you will analyze the performance of a concentrating photovoltaic (PV) system that also captures waste heat from the PV cell to produce power, a so-called hybrid power system. This system is proposed for a spacecraft designed to transport astronauts from the earth to the moon and back. The system is proposed as a means of vaporizing stored liquid oxygen for the crew and producing electrical power for spacecraft systems. The silicon back side of the thermoelectric module is cooled by vaporizing liquid oxygen at a pressure of 163 kPa. The back of the PV cell is bonded to the hot side of the thermoelectric model in such as way that the thermal conductance between them $\Lambda_{cont} (= A_{cont}\lambda_{eff} / \ell_{eff})$ is 300 W/K.

The 10 cm by 10 cm PV cell in this system sits on a support frame so that its surface normal is pointed directly at the sun as the spacecraft travels either to or from the moon. A control system keeps the PV surface normal to the sun's rays. Particularly relevant to this project are equations (14.16), (14.25) and (14.47) from the text (chapter 14):

$$\frac{P''}{\phi} = \frac{\pi^4 k_B T_{source}}{2.404(15)} \tag{14.16}$$

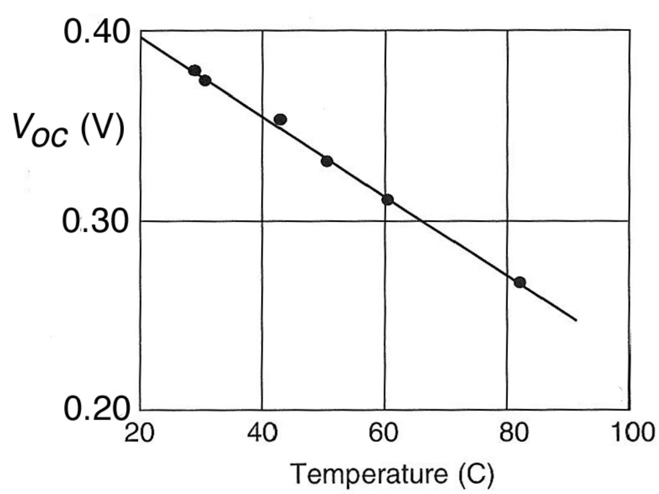
$$\frac{\phi_g}{\phi} = 0.416 \int_X^{\infty} \frac{x^2}{e^x - 1} dx \ , \quad \text{where} \ X = \frac{W_g}{k_B T_{source}} = \frac{hf_g}{k_B T_{source}} = \frac{q_e V_g}{k_B T_{source}} \tag{14.25}$$

$$V_L = \frac{k_B T_{pv}}{q_e} \ln\left[\frac{I_v - I_L}{I_0} + 1\right] - I_L R_s \tag{14.47}$$

where $I_v = \phi_g q_e A_{pv}, \quad A_{pv} = L_y L_z.$ (1)

Note that P'' here is the solar intensity incident on the PV cell, which is the unconcentrated direct solar intensity I_D for the cell surface multiplied by the concentration ratio r_c ($P'' = r_c I_D$ in W/m^2). Here r_c is initially taken to be 15 and the intensity of the incident solar radiation in space is 1080 W/m^2.

Task 1



Observed temperature variation of the open-circuit voltage.

Figure 2.

Using five points on the Fig. 2 plot between 20 °C and 100 °C, determine a linear curve-fit to V_{oc} ($V_{oc} = \hat{A} T_{pv} + \hat{B}$, T_{pv} in K). In Eq. (14.47), set $I_L = 0$ to get a relation for V_{oc}. Substitute the curve-fit relation for V_{oc} and rearrange to solve for I_0 / I_v. The resulting relation will allow you to compute I_0 / I_v as a function of temperature between 20°C and 100°C.

Task 2

Note that for a load with resistance $R_{L,pv}$, the operating point and the power delivered to the load are determined by simultaneously solving Eq. (14.47) and Ohms law:

$$V_L = I_L R_{L,pv} \tag{2}$$

Write a computer program that computes the power delivered by the PV cell as a function of $R_{L,pv}$ and the parameters in Eqs. (14.16), (14.25), and (14.47). It should also compute the PV cell conversion efficiency $\eta_{pv} = V_L I_L / (P'' A_{pv})$. Incorporate your curve-fit for I_0/I_v as a function of PV cell temperature T_{pv} to evaluate this ratio in equation (14.47). Determine the power output of the L_y = 10 cm by L_z = 10 cm PV cell for P'' equal to r_c = 15 times the unconcentrated incident radiation intensity I_D = 1080 W/m^2 and the following parameter values:

$R_{L,pv} = 0.0070\ \Omega$ $\quad$ $R_s = 0$

V_g = 1.1 V, f_g = 265 THz (for silicon) $\quad$ T_{pv} = 20°C and 80°C

Task 3

Now consider the thermoelectric module in the system. The temperature of heat input T_H is linked to the PV cell back side temperature T_{pv} by the heat transfer contact conductance relation across the interface between the PV cell and the thermoelectric module:

$$\dot{Q}_{pv} = \Lambda_{cont}(T_{pv} - T_H), \qquad \Rightarrow \quad T_H = T_{pv} - \dot{Q}_{pv} / \Lambda_{cont} \tag{3}$$

where $\dot{Q}_{pv}$ is the PV waste heat transfer rate. For steady state operation, the rate of heat input to the thermoelectric module $\dot{Q}_H$ must equal the rate of waste heat flow from the PV cell $\dot{Q}_{pv}$. The cold surface of the thermoelectric module transfers heat to vaporizing liquid oxygen. Liquid is drawn into the wick by capillary forces. Heat is transferred by conduction across the nickel wick with its pores filled with liquid oxygen. The wick is 4.0 mm thick (t_w = 4.0 mm). The effective thermal conductivity of the nickel wick filled with liquid oxygen is

$$k_{w,eff} = 6.5 \text{ W/mK}$$

In addition, the contact resistance at the interface between the thermoelectric unit and the evaporator is modeled as a conductance U_{ev} = 25 W/m^{2}K. Heat transfer to the liquid interface where vaporization occurs is therefore modeled as:

$$\frac{\dot{Q}_C}{A_{pv}} = \left[\frac{k_{w,eff}}{t_w} + U_{ev}\right](T_C - T_{sat}) \tag{4}$$

where T_{sat} is the saturation temperature of liquid oxygen at atmospheric pressure, $\dot{Q}_C / A_{pv}$ is the surface heat flux, and T_C is the temperature of the wall in contact with the wick. Thermodynamic data indicates T_{sat} = 95.0 K for oxygen at 163 kPa.

The thermoelectric module is to use a newly developed quantum dot superlattice material that is reported to have a figure of merit Z of 0.0114 K^{-1} between 20°C and 100°C. For the other thermoelectric properties of interest, use the following values:

Average Seebeck coefficient over temperature range of interest: α = 0.0017 V/K
Electric resistivity of arm A: ρ_A = 0.0020 Ω cm
Electric resistivity of arm B: ρ_B = 0.0030 Ω cm
Thermal conductivity of arm A: λ_A = 0.032 W/(cm K)
Thermal conductivity of arm B: λ_B = 0.021 W/(cm K)

The following equations derived from those in the lecture discussions are useful here:
Single pair electrical resistance and heat conductance:

$$R = \frac{\ell_A \rho_A}{A_A} + \frac{\ell_B \rho_B}{A_B}, \quad \Lambda = \frac{A_A \lambda_A}{\ell_A} + \frac{A_B \lambda_B}{\ell_B} \tag{5}$$

Note that for a battery of n thermoelectric pairs (there are 4 pairs shown in Fig. 1), the total battery electrical resistance is the product of n and the resistance of each pair (since the resistances are in series):

$$R_{batt} = nR \tag{6}$$

and the total thermal conductance of the battery is the product of n and the conductance of each pair (since the conductances are in parallel):

$$\Lambda_{batt} = n\Lambda \tag{7}$$

Voltage across the load with current flow for a battery of n thermoelectric material pairs:

$$V_L = n\alpha(T_H - T_C) - R_{batt} I_L \tag{8}$$

Rate of heat supplied from the high temperature source:

$$P_H = \dot{Q}_{pv} = \dot{Q}_H = n\alpha I T_H + \Lambda_{batt}(T_H - T_C) - \tfrac{1}{2} I^2 R_{batt} \tag{9}$$

Power output: $$\dot{W} = \frac{n^2 \alpha^2 (T_H - T_C)^2 R_{L,te}}{(R_{L,te} + R_{batt})^2} \tag{10}$$

Efficiency: $$\eta = \frac{\dot{W}}{\dot{Q}_H} = \left[\frac{T_H - T_C}{T_H}\right]\left[\frac{(1+m)^2}{m}\left(ZT_H\right)^{-1} + 1 + \frac{1}{2m}\left(1 + \frac{T_C}{T_H}\right)\right]^{-1} \tag{11}$$

where for a battery of n thermoelectric material pairs, the definition of m becomes

$$m = R_{L,te}/nR \tag{12}$$

and the figure of merit is still defined as: $$Z = \frac{\alpha^2}{R\Lambda} \tag{13}$$

Also, as shown in the text, the geometry choices that minimize $R\Lambda$ result in the minimum value given by

$$\left(R\Lambda\right)_{\min} = \left[\left(\lambda_A \rho_A\right)^{1/2} + \left(\lambda_B \rho_B\right)^{1/2}\right]^2 \tag{14}$$

And the value of $m = R_{L,te}/nR$ that maximizes the efficiency is given by

$$m_{max\,eff} = \sqrt{1+0.5(T_H + T_C)Z} \tag{15}$$

For specified values of the material properties and geometry ($\alpha, \lambda_A, \lambda_B, \rho_A, \rho_B, n$), $R_{L,te}$, T_H and T_{sat}, write a computer program that does the following:

First, sequentially compute the parameters listed below:

(a) the value of $(R\Lambda)_{\min}$

(b) the value of Z based on $(R\Lambda)_{\min}$

Then iteratively compute the values of T_C and $\dot{Q}_H$ that are required to satisfy Eqns. (4), (10) and (11). The following algorithm can be used to accomplish this:

(i) Guess T_C and compute

(a) the value of $m_{max\,eff}$

(b) the value of $R = R_{L,te}/nm_{max\,eff}$ (note this implies we will adjust the pair geometry to obtain an R value that results in $m = m_{max\,eff}$)

(c) the value of $\Lambda = (\Lambda R)_{\min}/R$ (note this implies we will adjust the pair geometry to obtain a Λ value that results in $\Lambda R = (\Lambda R)_{\min}$)

(ii) Use Eqn. (4) to compute $\dot{Q}_C = (\dot{Q}_C)_{boil}$.

(iii) Using the guessed T_C value, compute the efficiency η using Eqn. (11).

(iv) Compute the power output $\dot{W}$ from the thermoelectric device using Eqn. (10)

(v) Compute the heat input and rejection for the thermoelectric device using

$$\dot{Q}_H = \dot{W}/\eta \qquad (\dot{Q}_C)_{TE} = \dot{Q}_H - \dot{W}$$

(vi) Compute the error $E_{\dot{Q}_C}$ as

$$E_{\dot{Q}_C} = \dot{Q}_C)_{TE} - (\dot{Q}_C)_{boil}$$

If $\left|E_{\dot{Q}_C}\right| < 10^{-5}$, the calculation is complete and the resulting values of T_C and $\dot{Q}_H$ are the desired solutions. If not, a new value of T_C is generated and the process is repeated starting at step (ii).

(vii) Using the rate of heat supplied from high temperature source $\dot{Q}_H$ determined in the iterative calculation, use Eqn. (8) and (9) to determine the current to the load I_L, and the voltage across the load V_L for the specified parameters and computed parameters.

Use the program to calculate the needed parameters in steps (a)-(f) for the materials properties given above with $n = 12$, and $R_{L,te} = 0.10\ \Omega$, and for $T_H = 50\ °\mathrm{C}$, determine T_C, the power output of the module $\dot{W}$, $\dot{Q}_H$, $\dot{Q}_C$, the current to the load I_L, and the voltage across the load V_L.

Task 4

(a) Take the programs you wrote in Tasks 2 and 3, and combine them to generate a program to determine the operating point and performance of the hybrid system shown in Fig. 1. Determination of the operating point will require iterative solution of the governing non-linear equations to determine the PV cell operating temperature and the cold side temperature for the thermoelectric device. The following iterative scheme is recommended:

1. Guess T_{pv}.
2. Use the code developed in Task 2 to compute the power output of the PV cell $V_L I_L$ and the waste heat transfer rate $\dot{Q}_{pv} = P'' A_{pv} - V_L I_L$ for the guessed value of T_{pv}.

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3. Set T_H equal to

$$T_H = T_{pv} - \dot{Q}_{pv} / \Lambda_{cont}$$

and use the iterative scheme coded in Task 3 to determine the cold-side temperature T_C and the heat flow rate into the thermoelectric module $\dot{Q}_H$.

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4. Compute the error $E_{\dot{Q}}$ as

$$E_{\dot{Q}} = \dot{Q}_{pv} - \dot{Q}_H$$

If $\left|E_{\dot{Q}}\right| < 10^{-5}$, the computed values of the other operating point parameters are taken to be correct. If not, a new value of T_{pv} is generated and the process is repeated starting at step (2).

5. Once the value of T_{pv} is determined, other performance parameters for the PV cell and the thermoelectric module are to be computed: the load voltage, load current, power output and efficiency of the PV cell and thermoelectric module, and the combined power output and efficiency of the hybrid device.

The above iterative model calculation can be executed if $I_D, \alpha, \lambda_A, \lambda_B, \rho_A, \rho_B$, Λ_{cont} R_s, V_g, r_c, L_y, L_z, $T_{w,in}$, n, $R_{L,pv}$, and $R_{L,te}$ are specified. Write your computer program so that these parameters can be easily modified.

(b) Use your program to determine the operating point T_{pv} value and the efficiencies and performance parameters for the hybrid system with

I_D = 1080 W/m^2
r_c = 15
$L_y = L_z$ = 10 cm ($A_{pv} = L_y L_z$)
V_g = 1.1 V, f_g = 265 THz (for silicon)
R_s = 0
$R_{L,pv}$ = 0.0070 Ω
values of $\alpha, \lambda_A, \lambda_B, \rho_A, \rho_B$ specified in Task 3
Λ_{cont} = 300 W/K
T_{sat} = 90.2 K

$n, = 12$
$R_{L,te} = 0.10 \quad \Omega$

Task 5
In this task, take the parameter values listed above in Task 4 except for I_D and r_c. Note that I_D is the unconcentrated incident radiation intensity hitting the PV cell.

(a) Run your program with these parameter values with $r_c = 15$ and $720 \le I_D \le 1080$ W/m^2. From your results, determine and plot the variation of PV efficiency, thermoelectric module efficiency, and total system efficiency and power output over this range of I_D. (This assesses how performance will vary if the solar collector is not aligned perfectly.)

(b) Run your program with these parameter values with I_D = 1080 W/m^2 and $10 \le r_c \le 18$. From your results, determine and plot the variation of PV efficiency, thermoelectric module efficiency, and total system efficiency and power output over this range of r_c.

Task 6
In this task, take the parameter values listed above in Task 4 except for α, r_c and n.

(a) Use your program to evaluate the performance of the system for different combinations of concentration ratio r_c and number of thermoelectric pairs n, with $\alpha = 0.0017$ V/K , the value for the superlattice material. From these results, recommend values of r_c and n that provide the best design of a system that must meet the following specifications:

The design must have a total power output of 20 to 50 W (more is better).
Higher hybrid system conversion efficiency is better.
Smaller concentration ratio is better
Lower PV operating temperature is better.

Document all your design parameter choices and report the complete performance of the system for your design at the specified conditions. Justify your design choices with plots and/or tables summarizing your computed results.

(b) A proposal was made to eliminate the PV cell and deliver the solar energy directly to just the thermoelectric module. In this modified design, the concentrated solar energy will directly strike a highly absorbing nanocoating on the hot side of the thermoelectric unit, with 95% of the incident radiation absorbed into that surface. Modify your coded program to model this alternate system design and determine the operating point T_H and T_C values and the thermoelectric efficiency and performance parameters for this modified system design at the conditions specified in Task 4, part (b). Compared to the hybrid system analyzed in Task 4, part (b), what is the percentage loss in efficiency and power output performance for the system with the PV cell removed?

(c) (ME246 students only) Bonding the PV cell to the thermoelectric module is likely to produce thermal stresses as the unit cycles up and down in temperature over the course of a day's operation as a result of different thermal expansion characteristics of the thermoelectric materials and the PV materials. The resulting periodic stresses at the interface between these devices can result in failure of the PV cell or thermoelectric module, which are usually made of fragile semiconductor materials.

A proposed solution is to insert a thin layer of flexible yet high thermal conductivity material between the PV cell and the thermoelectric module and clamp the two devices together. So-called *thermal interface materials* are widely used to improve heat transfer from electronic chips to heat sinks. Search the internet for materials of this type, and their properties, and use your model to predict how some of them would perform, using a layer of appropriate thickness. Document the materials tested, their properties and predicted performance with your chosen film thicknesses in a table and/or plots. Include web site URL references for web sites where you found the materials information. Based on your exploratory performance calculations, identify a best candidate thermal interface material and film thickness, and assess how well this design strategy works as a solution of the thermal stress problem. Provide supporting results in tables and/or plots to justify your recommendations and assessment.

Tasks to be divided between coworkers:

(1) Assemble analysis for Tasks and algorithms for performance programs
(2) Implement algorithms into code and debug
(3) Run code to define design recommendation
(4) Analysis of results, plot or indicate trends in tables
(5) Write-up of results and conclusions

Deliverables:

Written final report should include:

(1) Written summary of how the work was divided between coworkers

(2) Analysis for Tasks requiring equation manipulation and documentation of analysis used to set up your computational scheme.

(3) A flow chart of the performance program used must be submitted. Reasoning behind the program structure should be described.

(4) Document your performance results for Task 5 in clear, well-organized plots, including units where appropriate

(5) Document design analysis results in plots for Task 6. Described how your plotted results or tables justify your design choices. ME 246 students, be sure to provide plots, tables, and web references for your materials as requested for Part (c) of Task 6. A copy of your program should be attached to the report as an appendix.

(Deliverables **due Thursday 10/25/18 in class, by 5:00 pm electronically or in drop box**)

Grade will be based on:

(1) thoroughness of documentation of your analysis and results
(2) accuracy and clarity of interpretation
(3) thoroughness of the design investigation and the documentation of the reasons for your design choice