THERMOPHOTOVOLTAIC SYSTEM PARAMETRIC MODELLING

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ABSTRACT

A small radioisotope powered TPV system was assumed. The system was simplified into a one-dimensional model with the emitter and heat rejection system as boundaries. Design equations were then developed which would allow parametric modelling of system efficiency, emitted radiation incident upon the TPV cell, energy converted in the TPV cell, and energy absorbed in the filter and cell-to-cell gaps. A figure of merit was then developed for the emitter, filter and TPV cell.

INTRODUCTION

The thermophotovoltaic (TPV) generator is an emerging technology which received attention ovar a 30 year period but has never reached commercialization. Numerous theoretical medals have been presented in the past [1 -51. However these models do not 90 into sufficient material and component detail to allow sensitivity analyses and component performance tradeof fs.

Advances made in the last decade permit the cost effective fabrication of low band gap photovoltaic materials, dichroic filters, and plasma filters. With these new components it is now reasonable to model a TPV system with the expectation that the required components can be customized. Actual design and fabrication of many of the needed TPV system components is already proceeding at a rapid pace. The only drawback to this scenario is that there is a lack of analytical tools needed to guide the optimization of TPV system performance. Now that there has been sufficient exploratory work, the creation of these needed analytical tools is an appropriate and cost effective response.

The major modelling effort will be on the optical cavity. Areas to be covered are: multiple reflections from emitter, filter, and cell; cell spectral response as a function of temperature and intensity; voltage temperature and intensity coefficients; currant series resistance effects due to intensity; creation of figures of merit; and use of parametric sensitivity analyses.

DEFINITIONS

Assume that the emission is in a narrow enough wavelength band so that properties fike emissivity, absorptivity, and reflectance are constants unchanging with multiple reflection,

ρ_c = TPV cell reflectance
ρ_f = filter reflectance
ρ_g = call plane gap reflectance
a, = filter internal absorptance
ϵ = emitter surface emissivity = absorptivity
(1 -ϵ) = reflectance
F_{ec} = view factor from emitter to cells
F_{ce} = view factor from cells to emitter
γ_i = fraction of emitter radiation at emitter temperature T, which lies in the i^{th} wavelength band
P = TPV cell optical packing factor

Note: While most optical parameters are assumed to be wavelength dependent this is not shown above and in many of the equations for simplicity and brevity.

APPROACH

A simple system model was sought in order to ease the mathematical treatment of the major system components: emitter, optical cavity, and heat rejection system. The optical cavity is viewed as being bounded by the emitter and tha heat rejection system which are just planes in space with surface properties but no mass.

System Design Requirements

The emitter, filter, and TPV cell are difficult to specify since they are interrelated and dependent upon required output power density and level of heat input. Other design issues that need to be addressed in a complete model, but are not addressed here, are: parasitic heat losses due to end effects; TPV array losses due to cell mismatch end emitter planar temperature variation; shadowing and heat losses due to cell metallization and bus bars; and long term effects due to radiation damage and surface optical degradation.

Some areas where themodelling effort can be relaxed are: effect of load changes on TPV system operation (this can be handled by the power system); effect of heat rejection system efficiency due to distance from sun; and cell and material aging effects. These are real but not pressing issues.

The optical cavity is assumed to consist of an emitter, a cell-mounted filter, and TPV cells with gaps in between. The optical cavity parameters of interest are: the emitter spectral emissivity; the filter reflectance and absorptance; emitter/filter/cell multiple reflection effects; TPV cell reflectance; TPV call spectral response as a function of temperature; TPV cell efficiency as a function of intensity and temperature; and TPV cell metallization and interconnect reflectance (which could be incorporated into tha cell gap reflectance value).

Component Requirements

The TPV system components of interest are: emitter, filter, cell, and heat rejection system. A change made in any one component will generally place different requirements on all other components. This interdependence leads to a requirement for parametric modelling and sensitivity studies,

Emitter - the emitter is located between the heat source and the filter. Emitter requirements are tha ability to transform conducted heat into radiated energy of appropriate spectral character. The emission spectrum will be dependent upon temperature as well as material and surface properties and therefore will be modeled either mathematically as a gray body or by interpolation between tabular values derived from experiments made at different temparatures. Temperatures of the heat source and the emitter surfaces ara assumed to be constant. Other emitter requirements ara adequate mechanical properties, retention of optical properties with time, and low volatility at operating temperature.

Falter - the filter is located between the emitter and the cell and modifias the photon spactrum. Tha requirements placed upon the filter are thus dependent upon the emitter spectrum and TPV cell spectral response. Filter basic design requirements are the ability to reflect photons with unwantad energy levels and transmit the remaining photons with low absorbance. An additional complexity is the need to include the capability to shape the filter pass-band to balance the power density requirement with available heat. Filter parameters ara assumed to be independent of temperature since thay are cell mounted and will only sae temperatures of about 30-80 ‘C. Other filter requirements are adequate mechanical properties and retention of optical properties with time.

Cell - the cell is located between the filter and the heat sink and is viewad as a transducer with a spectral rasponse for conversion of photons of various energy levels to electrons. The TPV cell spectral responsrr can either be basad upon measured or theoretical values as long as temperature effects are included. This is avan more important with regard to TPV cell conversion efficiency since low band gap cells have large voltage-temperature coefficients and the intensity effect is also large since TPV systems may run at 100+ suns. The temperature drop across the filter-TPV cell-heat rejection system combination is likely to be small in a good design but can not be neglected at the axpected operating intensity level. Cell basic design requirements are bandgap matched to emitter spectrum, good spectral response, low series resistance, and low dark current. Other design considerations are cell-to-cell interconnection, cell size, and thermal grounding.

Heat Rejection System - the heat rejection systam is located betwaen the cell and outer space and has to be sized to handle all heat energy not converted to electricity. The heat rejection system consists of two different surfaces: those that are covered by the TPV cells and thermally coupled to them; and thosa gaps between cells which are exposed to radiant energy from the emitter. The heat rejection system is dependent upon view factors and spacecraft orientation as well as material proparties which are subject to mass limitations so a model was not pursued. The heat rejection system is temperature dependent and could be modeled by using SINDA [61 or some other finite difference analysis tool, however, lack of funding has prohibited completion of this part of the effort. Heat sink design requirement is ability to dissipate heat at a given design temperature. Other design considerations are low mass, high heat transfer rata, and spacecraft storage, These othar requirements are not coverad here.

System Efficiency

The system under consideration starts with the emitter surface and ends with the haat rejection systam. A common statement of TPV system efficiency is: $\eta = E_{out}/E_{in}$. This is essentially correct but does not provide enough focus. An improved statement is: $n = (E_c-E_{ss})/E_{in}$, where E_c is the energy converted by the cell to electrons and E_{ss} is the energy required to run all of the subsystems required for energy conversion. Of special interest is the relationship between the heat rejected $(1 -E_c)$ and E_{ss} since a lower conversion efficiency implies a higher heat rejection load and therefore a more required E_{ss}. This line of reasoning can be extended to passive heat rejection systems by utilizing additional mass and additional cost es penalty criteria. The above example shows that simple analyses must be viewed with caution. It is possible to only look at the heat producing system or the heat rejecting system apart from the rest of the TPV system as long as overall system efficiency issues are addressed. It is impossible to separate the elements of the TPV optical cavity. Here the level of interaction is too high. Hottel, in Part II of Ref. 7, has done an excellent analysis of the optical system for a fibrous emitter and a continuous TPV cell plane. The analysis here uses the same approach as Hottel but assumes a solid emitter; a filter (or composite set of filters) instead of a shield; and a discontinuous TPV cell plane with packing factor, P. The emitter will first be discussed separately and then as part of the optical cavity of the TPV system.

Emitters can be separated into three general classes: gray body, selective, and band-pass. A gray body is used for emitters which have an emission spectrum similar to tha Planck black body spectrum. The gray body is used since a large area black body can not be made economically. Emissivity of a gray body for a TPV system should be = > 0.8.

A selective emitter (usually a rare earth oxide) would seem to be ideal for TPV systems, however, there are some problems. First the peak emissivity of a selective emitter is usually low (<0.7), Second, the total energy under the emissivity curve is usually low due to narrow band width and low emissivity. Low energy density lowers tha TPV call conversion efficiency and usually leads to some sort of optical concentration system being required. Third, the rare earth oxides are fragile in bulk and must be made into fibers for application. Fourth, many of the rare earth oxides have secondary emission peaks. Despite these problems, the reduced demands upon subsequent filters may lead to an optimal TPV system using a selective emitter.

Band-pass emitters have not bean discussed much in the recent TPV literature, however, they should not be overlooked. A band-pass emitter is any material which exhibits a non-black body spectral distribution. A selective emitter is an extreme example of a band-pass emitter. Some specular metal surfaces, such as polished tungsten, have been shown to have an emission spectrum which is a very good match for some TPV cells. The resultant radiation incident upon the TPV cells is:

$$It(l)=PF_{ec}\frac{\epsilon\gamma(1-\alpha_f-\rho_f)}{D} \qquad (1)$$

where D is defined to be:

$$D=1-\rho_f[P\rho_c+(1-P)\rho_g][1-F_{ec}F_{ce}(1-\epsilon)] \times \left[\rho_f+\frac{[P\rho_c+(1-P)\rho_g](1-\alpha_f-\rho_f)^2}{1-\rho_f[P\rho_c+(1-P)\rho_g]}\right] \qquad (2)$$

$S(\lambda_1-\lambda_2)$ is tha measured spectral response of the TPV cell and $F(I_c)$ is a function dependent upon intensity which changes the conversion efficiency of the TPV cell. Factors involved in $F(I_c)$ are: V_{oc} increases logarithmically with intensity; cell temperature, T_c, rises linearly with intensity assuming constant thermal conductivity, k_c, which reduces V_{oc}; cell series resistance, R_s, and wire resistance, R_w, losses rise as the square of current which is linearly proportional to intensity; cell bandgap decreases as temperature rises so the current temperature coefficient increases. The F(IJ function then could be stated as:

$$F(I_c)=a_1\log(I_c)(1-a_2I_ck) \times I_c^2(R_s+R_w)a_3I_ck \qquad (3)$$

where al, a_2, and a_3 are temperature dependent coefficients of the TPV cell. Energy converted in the TPV cell then is:

$$E_c=\Sigma_1^2\ I_c(\lambda)S(\lambda_1-\lambda_2)F(I_c) \qquad (4)$$

end energy incident upon the cell is:

$$E_i=\Sigma_0^\infty\ I_c(\lambda) \qquad (5)$$

The filter acts to reflect unwanted radiation to the emitter and absorbs some of the radiation as shown:

$$A_f=F_{ec}\alpha_f\sum_0^\infty\frac{N}{D} \qquad (6)$$

where N is:

$$N=\epsilon\gamma\left(1+\frac{[P\rho_c+(1-P)\rho_g](1-\alpha_f-\rho_f)}{1-\rho_f[P\rho_c+(1-P)\rho_g]}\right) \qquad (7)$$

The energy lost due to the gaps in the cell plane is:

$$A_g=\Sigma_0^\infty I_c(\lambda)(1-\rho_g)(1-P) \qquad (8)$$

If end, conduction, and convection losses are all ignored for simplicity, the total energy to be handled by the heat rejection system then is:

$$E_r = A_f + A_g + (E_i - E_c) \qquad (9)$$

Figures of Merit

Figures of merit are an excellent way to focus materials development effort, An emitter figure of merit can be developed for a TPV cell by assuming that an ideal emitter would only radiate in the wavelengths where the TPV cell efficiently converts the radiation to electrons. It is also implied that the ideal emitter can not absorb any radiation outside of the desired band, Neglected in this definition are any intensity effects which would have to be determined from Eq. 3 above. The emitter figure of merit could then be stated as:

$$FM_e(T) = \frac{\Sigma_1^2\ \epsilon(\lambda) S(\lambda_1 - \lambda_2)\gamma_i}{\Sigma_0^\infty\ \epsilon(\lambda)\gamma_i} \qquad (10)$$

Since the emissivity is temperature dependent the emitter figure of merit is also temperature dependent.

The figure of merit for a filter is achieved by assuming that the ideal filter would pass all radiation in the wavelengths where the TPV cell efficiently converts the radiation to electrons and would pass no radiation outside of this band. The filter would also have zero absorptance in this band. The filter figure of merit could then be stated as:

$$FM_f(T) = \Sigma_1^2\ \epsilon(\lambda)(1 - \rho_f(\lambda))S(\lambda_1 - \lambda_2) \qquad (11)$$
$$\times\, \gamma_i(1 - \alpha_f(\lambda))/(A_f + E_i)$$

The figure of merit for a TPV cell is based upon an ideal cell which converts all incident radiation and has no internal losses. In order to provide a consistent radiation source for the figure of merit a black body emitter at expected system operating temperature is assumed. Since the emitter and filter are the system components which shape the spectrum, no spectral changes are assumed here and the range of integration is only over the spectral response range.

$$FM_c(T,I) = \frac{\Sigma_1^2\ E_{\lambda b} S(\lambda_1 - \lambda_2)}{\Sigma_1^2\ E_{\lambda b}} \qquad (12)$$

where $E_{\lambda b}$ is Planck's law:

$$E_{\lambda b} = \frac{2\pi h c^2 n^2 \lambda^{-5}}{e^{\frac{hc}{k\lambda T}} - 1} \qquad (13)$$

where h is Planck's constant, c is speed of light, k is Boltzmann's constant, n is index of refraction of emitter, and T is temperature in Kelvin. Note that the emitter index of refraction is a parameter.

RESULTS

Equations were developed to allow sensitivity analyses of components of a small radioisotope TPV system.

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