COMPARISON OF OPTIMIZATION OF MULTICOLOR AND FOUR-COLOR PHOTOTHERMAL POWER PLANTS IN THE SOLAR SYSTEM - A REVIEW

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Contents

Summary

The chapter deals with the performance of photothermal multicolor and omnicolor converters in the Solar System. The case of four-color photothermal converters is also considered. Both interplanetary power stations and power systems placed on the surface of different planets are analyzed. The power stations consist of a multicolor converter – endoreversible thermal engine combination. In case of ground based planetary stations the thermal engine is assumed to be of the Chambadal-Novikov-Curzon-Ahlborn type. The interplanetary stations, which are characterized by a nonlinear heat transfer between the engine and the environment, are treated by using a simple model. The influence of the radiation concentration on the system performance is outlined. The effect of the sun zenith angle is also discussed. Spectral distributions of the collector and radiator optimum temperatures are shown.

1. Introduction

Several early studies have identified a series of advanced space missions that need versatile, high-capacity space power systems (Angelo and Buden, 1986; NASA, 1989). These missions include manned planetary outposts and bases for sustained operations (hundreds of kW to MW power levels), and interplanetary cargo vehicles with requirements in the 2-5 MW power range (Angelo and Buden, 1991). It is expected that the development of humanity's extraterrestrial civilization and the full and complete exploration of our Solar System will be accompanied by the extensive use of progressively more sophisticated space power systems (Angelo and Buden, 1991). Solar radiation is, of course, one of the main candidates as an energy source for advanced space missions, while the omnicolor solar converters, which will be studied in this chapter, are perhaps the highest technology we could envisage in this area. Presently, there are two major types of solar power system used in space missions. The first type uses photovoltaic cells to convert the solar radiation directly into electrical energy, in combination with electrochemical storage. The second type is the so called “dynamic” system, in which solar concentrators reflect the flux of solar radiation towards a collector where a working fluid is heated up to drive conventional thermal engines. Electrical energy could then be generated by alternators coupled to these engines. Both types of solar power system will be considered in this chapter.

2. Omnicolor Photothermal and Photovoltaic Converters

Various authors have proposed different ways to convert solar energy into useful work. In the case of photovoltaic conversion, Shockley and Queisser (1961) treated a single cell (i.e. consisting of a single gap semiconductor). They have calculated a thermodynamic efficiency limit of 30% for such a cell. However, it has been soon realized that the use of a system involving more than one energy gap should enable to produce solar cells having much higher efficiencies.

It is believed that the highest efficiency can be realized by an infinite stack of p-n junctions with smoothly varying band gaps from infinity to zero, such that there is a single junction adapted to each frequency in the solar spectrum. In the system proposed by De Vos (1980) all individual cells are selective black bodies such that the photons of frequency ν of the solar spectrum are completely absorbed by the cell with bandgap $E_{\mathrm{g}} = h\nu$. Such a system is denoted as a “fully selective” or “omnicolor” photovoltaic converter. Useful approximations for their mathematical treatment were proposed subsequently by Grosjean and De Vos (1981). A small error in the model was corrected by De Vos and Pauwels (1981) and Pauwels and De Vos (1981) who outlined a simple relation between the Carnot efficiency of thermodynamic engines and photovoltaic energy conversion. A new improvement of the model was performed by De Vos and Vyncke (1983) who introduced the influence of the ambient radiation and proved that both photovoltaic and photothermal “omnicolor converters” (a denomination which they proposed) have the same maximum efficiency. The influence of radiation concentration on the efficiency of omnicolor converters was studied by Haught (1984). Note that the geometric factors affecting the ambient radiation incident on the collector have to be corrected in that paper. However, this error has little influence on the results. Some of the above papers were reviewed in two books (Sizmann, 1990; De Vos, 1992).

This chapter provides an introduction to the thermodynamics of photothermal (PT) and photovoltaic (PV) omnicolor converters (Badescu and Dinu, 1995). A unifying approach is also presented (Badescu, 2017).

Usage of highly (or even fully) selective collectors is more attractive for cosmic applications than for Earth applications. Indeed, the risks and lack of chance to correct possible damage during space missions require the usage of the most sophisticated human technologies. From this point of view multi-junction cells are serious candidates (Toussaint, 1991; Verie et al., 1991). This chapter deals with the performance of omnicolor converters in the Solar System. Both photothermal and photovoltaic converters are envisaged. Our analysis refers, on one hand, to interplanetary space power stations and, on the other hand, to power systems placed on the surfaces of different planets. The influence of radiation concentration on system performance is outlined for some cases of practical interest. The effect of the radiation incidence angle is also discussed. Spectral distributions of the thermal collector optimum temperature and photovoltaic cell optimum voltage have been presented for the first time by Badescu (1995).

2.1. Omnicolor Photothermal Converters

The maximum conversion efficiency with a thermal system is obtained, in the limit, with an infinite collector array, as shown in Figure 2. Each radiation splitter selects from the (concentrated) radiation spectrum the photons from a narrow band of width $d\nu$ around a given frequency ν used to heat a collector that absorbs and emits around that frequency. This collector has a temperature $T_c(\nu)$ and its absorptance $\alpha(\nu)$ is supposed to be given by

$$\alpha(\nu)=\begin{cases}1 & \text{for } \nu\in\left[\nu-d\nu/2,\nu+d\nu/2\right]\\ 0 & \text{for all other frequencies}\end{cases}. \qquad (1)$$

The spectral irradiance φ from a source of blackbody radiation at temperature T may be written in the form:

$$\phi(\nu,T)=\frac{B}{\pi}I_P(\nu,T), \qquad (2)$$

where B is the geometric factor and

$$I_P(\nu,T)=\frac{2h\nu^3}{c^2}\left[\exp\left(\frac{h\nu}{kT}\right)-1\right]^{-1} \qquad (3)$$

is Planck‘s distribution.

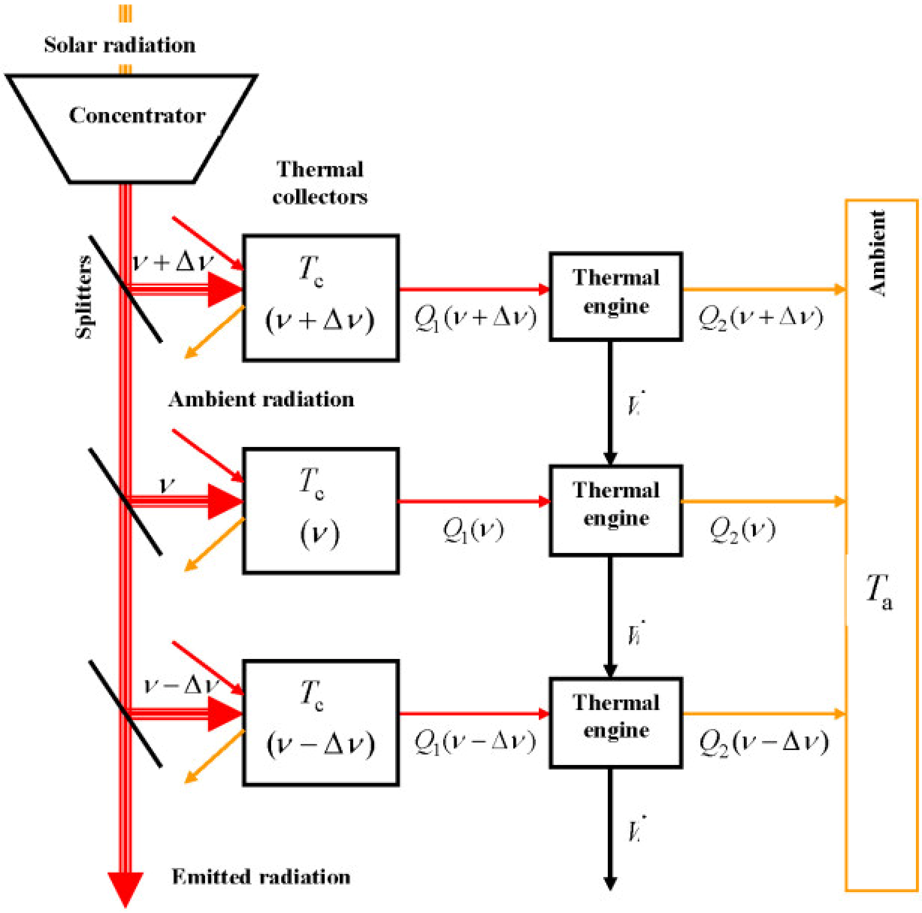

Figure 2. Omnicolor PT converter.

The net thermal flux $\dot{Q}_1(\nu)$ supplied by the collector of surface area A at temperature $T_c(\nu)$ toward its accompanying heat engine is supposed to be given by

$$\dot{Q}_1(\nu)/A = \phi_s(\nu, T_s) + \phi_a(\nu, T_a) - \phi_c\left[\nu, T_c(\nu)\right], \tag{4}$$

where the subscripts s, a, and c refer to the Sun, ambient, and collector, respectively. The first two terms from the right-hand side of Eq. (4) represent the incident solar and ambient radiation, respectively, while the last term is the flux of radiation emitted by the collector. In a first approximation, the Sun can be considered as a source of isotropic radiation. In this case, $T \approx 5760\ \mathrm{K}$. Figure 1 illustrates the gemometry of local setup and of the location of the collector on the planet with reference to the Sun.

The following equation applies for the geometric factor of the Sun:

$$B_s(\Omega_s, \theta_0) = \pi\, b^2(\Omega_s)\cos\theta_0, \tag{5}$$

where:

$$b\left(\Omega_s\right)=\left[\frac{\Omega_s}{\pi}\left(1-\frac{\Omega_s}{4\pi}\right)\right]^{1/2}=\sin\delta\,. \tag{6}$$

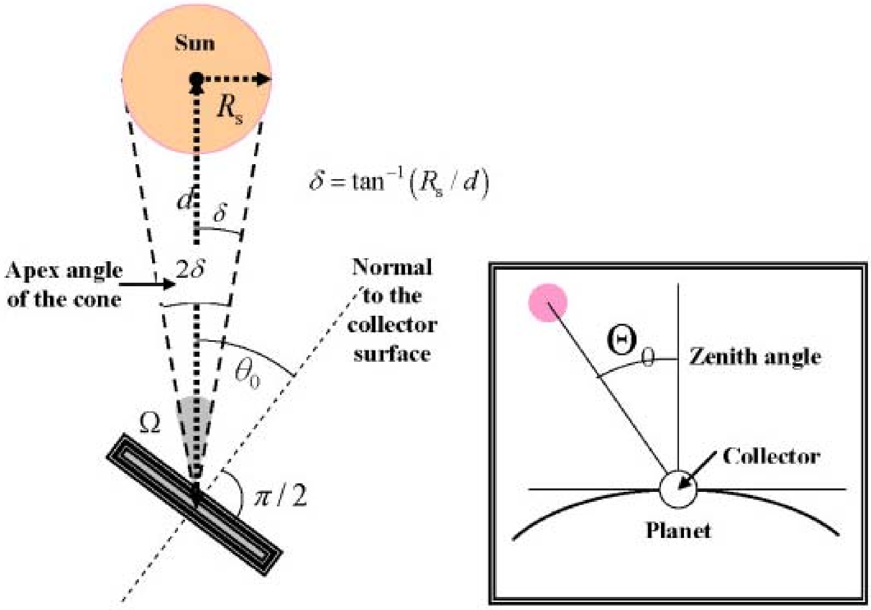

Figure 1. Geometry of the local setup and of the location of the collector on the planet with reference to the Sun

Here, Ω_s is the solid angle subtended by the Sun when viewed from the receiving surface, while θ_0 is the angle between the normal of the receiving surface and the direction to the center of the solar disc (i.e., the Sun's zenith angle). Also, δ is the half-angle of the cone subtended by the Sun. Equation (5) can be used only when the following condition is fulfilled,

$$\theta_0+\delta\le\pi/2\,, \tag{7}$$

that is, when the sun is completely visible.

When unconcentrated direct solar radiation is considered, the solid angle Ω_s subtended by the Sun can be computed by Eq. (6), by taking into account the simple geometrical relationship $\delta=\tan^{-1}\left(R_s/d\right)$ where $R_s\left(\approx 6.9599\cdot 10^5\,\mathrm{km}\right)$ is the Sun's radius and d is the distance of the Sun from the earth) as viewed from the collector. (The sun is seen from the earth at an average angular diameter of 0.5334 degrees or 9.310×10^{-3} radians. The solid angle subtended by a cone with an apex angle 2δ, $\Omega=2\pi\left(1-\cos\delta\right)$ $=6.807\times10^{-5}$ steradians or 0.000542% or 5.42 ppm.) (Figure 1) . In the case of concentrated radiation, first we observe that in the presence of the concentrator, the Sun is viewed from the collector surface as having an enlarged solid angle (say Ω_c). The concentration ratio C is naturally defined as (Landsberg and Baruch, 1989):

$$C = \frac{B_s\left(\Omega_c, \theta_0 = 0\right)}{B_s\left(\Omega_s, \theta_0 = 0\right)}, \tag{8}$$

that is, the ratio between the geometric factors of the concentrated and the nonconcentrated radiation, respectively, both evaluated at normal incidence ($\theta_0 = 0$). By using Eqs (5-8), one obtains

$$C = \frac{\Omega_\mathrm{c}\left(4\pi - \Omega_\mathrm{c}\right)}{\Omega_\mathrm{s}\left(4\pi - \Omega_\mathrm{s}\right)}. \tag{9}$$

Consequently, for a given distance to the sun and concentration ratio C, Eq. (9) can be used to compute the enlarged solid angle Ω_c. Then, the energy flux density $\varphi_\mathrm{s}\left(\nu, T_\mathrm{s}\right)$ can be evaluated by means of Eq. (2). The geometric factor B_a of the ambient radiation flux is given by Landsberg and Baruch (1989):

$$B_\mathrm{a} = \pi - B_\mathrm{s}. \tag{10}$$

Note that Eq. (10) is rigorous in the case of concentrated solar radiation, when the concentrator mirror covers part of the celestial vault (Badescu, 1992). However, this equation is a very good approximation in the case of unconcentrated radiation too, because of the negligible value which B has in this case (at the mean Earth–Sun distance $B_\mathrm{s} \approx 6.83 \times 10^{-5}$). Equation (10) was accepted by several authors (De Vos and Vyncke, 1983; Haught, 1984). Haught (1984) adopted the following assumption: $B_\mathrm{a} = \pi$. We proved that each of the two hypotheses is valid under special circumstances (Badescu, 1992). Throughout this section, we accept Eq. (10) because Haught's assumption $B_\mathrm{a} = \pi$ could lead to significant error for large values of C.

The collector is supposed to emit radiation toward the whole hemisphere ($\Omega = 2\pi$); consequently, its geometric factor is $B_\mathrm{c}\left(\Omega = 2\pi, \theta_0 = 0\right) = \pi$, as Eq. (5) shows. By using Eqs. (2), (3) and (10), we obtain the net thermal flux $\dot{Q}_1(\nu)$ entering the thermal engine working at frequency ν:

$$\dot{Q}_1(\nu)/A = \frac{2\pi h\nu^3}{c^2}\alpha(\nu)\left\{\begin{array}{l} \dfrac{B_\mathrm{s}}{\pi}\left[\exp\left(\dfrac{h\nu}{kT_\mathrm{s}}\right) - 1\right]^{-1} \\ +\left(1 - \dfrac{B_\mathrm{s}}{\pi}\right)\left[\exp\left(\dfrac{h\nu}{kT_\mathrm{a}}\right) - 1\right]^{-1} - \left[\exp\left(\dfrac{h\nu}{kT_\mathrm{c}}\right) - 1\right]^{-1} \end{array}\right\}. \tag{11}$$

If we take into account Eq. (1), we see that this engine uses the energy of solar radiation in a narrow range around frequency ν only. Of course, the neighboring engines use the radiation from other infinitesimal frequency intervals. In this section, the thermal engines are supposed to be of Carnot type. The power provided by the engine working at frequency ν is given by $\dot{W} d\nu = \dot{Q}_1(\nu)\eta_{\text{Carnot}} d\nu$, where η_{Carnot} is Carnot efficiency. Consequently, the mechanical power W_{tot} supplied by the array of monochromatic converters (i.e., by the whole omnicolor converter) can be obtained by summing up the contributions of all thermal engines:

$$\dot{W}_{\text{tot}} = \int_0^\infty \dot{W}(\nu) d\nu = \int_0^\infty \dot{Q}_1(\nu)\left[1 - \frac{T_{\text{a}}}{T_{\text{c}}(\nu)}\right] d\nu . \tag{12}$$

Remember that $\dot{Q}_1(\nu)$ is a function of $T_{\text{c}}(\nu)$. The maximum power supply $\dot{W}_{\text{tot,max}}$ can be obtained by optimizing the collector temperature $T_{\text{c}}(\nu)$ for conversion of the radiation of frequency ν. Consequently, to obtain the maximum power we have to solve the following equation:

$$\frac{\partial \dot{W}_{\text{tot}}}{\partial T_{\text{c}}(\nu)} = 0 , \tag{13}$$

and then replace its root (say $T_{\text{c,opt}}(\nu)$) in Eq. (11). The maximum efficiency of the omnicolor PT is simply given by

$$\eta_{\text{PT,max}} \equiv \frac{\dot{W}_{\text{tot,max}}}{\int_0^\infty \phi_{\text{s}}(\nu) d\nu} = \frac{\dot{W}_{\text{tot,max}}}{\frac{B_{\text{s}}}{\pi}\sigma T_{\text{s}}^4} . \tag{14}$$

An omnicolor PT converter yields $\eta_{\text{PT,max}} = 0.868$ for terrestrial applications, and even higher efficiencies in case of some space applications (due to the lower environmental temperature).

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Biographical Sketch

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