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A STUDY OF THERMAL EXCHANGE IN A THERMOPHOTOVOLTAIC
(TMV) SYSTEM AT MODERATE TEMPERATURE

by

Yan Xu Graduate Student

Bachelor of Science
University of Nevada, Las Vegas
1996

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of the requirements for the degree of

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in

Mechanical Engineering

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Examination Committee Chair

Dean of the Graduate College

Examination Committee Member

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ABSTRACT

A Study of Thermal Exchange in a Thermophotovoltaic (TPV) System at Moderate Temperature

by

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A numerical simulation study is reported on the thermal exchange in an evacuated parallel-plate system consisting of an emitter and a photovoltaic (PV) material with the emitter temperature between 350K and 550K. Although higher temperature (and thus higher power output) thermophotovoltaic systems have been of interest previously, the focus here is on systems that can not achieve high temperatures, like micromachines. The study examines the electrical power output and power generation efficiency for four kinds of emissivity variations for the heat source coupled with three different compounds of In_{x}\text{Ga}_{1-x}\text{As} PV materials. The results show that a 25\% Ho YAG thin film selective emitter coupled with an In(0.72)Ga(0.28)As material has the highest power generation efficiency for actual materials. These values are between 28\% and 34\%, depending upon the temperature. Also, the ideal cases that yield the potential maximum electrical power output and power generation efficiency for this temperature range are discussed.
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NOMENCLATURE

c_o : The speed of light in vacuum, 2.998 \times 10^8 \text{ m/s}
E : Emissive power, W/sq.m
E : Photon energy, eV
E_g : Bandgap of PV material energy, eV
h : Planck Constant, 6.6256 \times 10^{-34} \text{ Js}
k : Boltzmann Constant, 1.3805 \times 10^{-23} \text{ J/K}
k : Extinction coefficient
n : Index of refraction
P : Electrical power output, W/sq.m
q : Net heat transfer, W/sq.m
q_o : Radiosity, W/sq.m
T : Absolute temperature, K

Greek

\alpha : Absorptivity
\varepsilon : Emissivity
\eta : Power generation efficiency
\eta_e : Carnot cycle efficiency
\eta_{\text{ex}} : External quantum efficiency of PV material
\lambda : Wavelength, \mu\text{m}
\rho : Reflectivity
\sigma : Stefan - Boltzmann constant, 5.670 \times 10^8 \text{ W/sq.m K}^4
Subscript

1 : Selective emitter surface
2 : PV material surface
b : Blackbody
f : End of the wavelength range
i : Incident
i : Beginning of the wavelength range
o : Leaving spacing
λ : Wavelength
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CHAPTER 1

INTRODUCTION

The concept of thermophotovoltaic (TPV) energy conversion has been studied about thirty years. The TPV concept utilizes a converter (a semiconductor photovoltaic cell and an emitter) to convert radiant energy from a heat source to electrical power.

The thermophotovoltaic (TPV) energy conversion system is comprised of two main components: a heat source and a converter. The thermal energy from the heat source is converted to electricity by the converter.

In the most common applications, the heat from the sun (at 5790 K) is incident upon a photovoltaic cell (or solar cell) and this produces electricity (Merrigan, 1975). However, the term TPV is usually reserved for applications involving nonsolar radiant heat sources (Horne et al. 1995). A wide range of fuels can drive nonsolar radiant heat sources including various fossil sources, nuclear, and renewable energy. This is a key advantage relative to a solar energy source that is a primary alternative in many potential applications (Benner et al. 1995) such as:

- remote electricity supplies
- transportation
- co-generation
Photovoltaic energy conversion is a process where photons of light energy are converted into electrical energy directly. When a photon of sufficient energy is absorbed in a semiconductor, this frees an electron from the crystalline lattice bond, and an electron hole pair is produced. The minimum energy required is equal to the bandgap energy (Eg) of the semiconductor. The conversion efficiency depends on the wavelength of the incident radiation. If the wavelength of the incident energy is longer than the wavelength of the bandgap energy (Eg) of the semiconductor (the incident energy is less than the bandgap energy), conversion does not occur. No electrical power can be generated in this case. If the wavelength of the incident energy is less than the wavelength of the bandgap energy of the semiconductor (the incident energy is large than the bandgap energy), electrical power can be generated. However, any energy in excess of the bandgap energy is converted less efficiently and contributes to thermal energy lost from the process. So, the best conversion occurs for photons just exceeding the bandgap energy of the semiconductor.

A converter consists of a photovoltaic (PV) cell, and either a wide-band emitter with bandpass/ infrared reflector filter or a spectrally selective emitter. The wide-band emitter emits photons in a broad spectrum while the selective emitter emits photons in a narrow emission band to match the bandgap of the PV cell.

The converter component plays a very important role in the TPV energy
conversion system. There have been many theoretical and experimental studies of a converter from either the PV cell side or the emitter side.

The first TPV converter was built by Werth in 1963 using germanium PV cells and a propane-fueled emitter at a temperature around 1700 K (Werth, 1963). In 1980, Swanson reported a measured TPV conversion efficiency of 29% using silicon PV cells and a 2300 K wide-band emitter (Swanson, 1980). During the recent several years, with the technological development of the III-V semiconductor in the photovoltaic cells side (Wilt et al. 1994 and McNeely et al. 1994) and the application of the rare-earth elements to the selective emitter side (Adair et al. 1994 and Lowe et al. 1994), a converter with higher electrical power output density (around 3 - 4 watts cm^-2) was built (Coutts et al. 1996). Also, TPV power sources in the range of 150 to 500 watts were developed by Thermos Power Corporation, with funding support from DARPA / NASA - Lewis (Becker et al. 1997).

However, there exists a common point in the above studies. The temperature range in the emitter side is from 1000 K to 2500 K. Most applications strive for high electrical power output, and high temperatures are needed for this. On the other hand, there could be applications, e.g. micromachines, where high temperatures can not be tolerated. What will happen if the temperature range in the emitter side drops to 350 K to 550 K? What electrical output power densities can be generated with the same converter, which was used in the temperature range 1000 K to 2500 K? What power generation efficiency can be achieved? What is the relationship between the PV cell bandgap and the emitter spectrum in the lower temperature range? What are directions
to find new materials in both the PV cell side and the emitter side?

A search of the literature did not show any papers focused on this lower temperature range. This study focuses on the above questions from the perspective of the radiative heat transfer. The thermal analysis given here is based on the documented characteristics of PV cells and emitters.

From the manufacturing point of view, a flat plate system is easily manufactured and assembled for both the PV cell side and the emitter side. The thermal analysis is based on an evacuated flat parallel-plate geometry. One side is a photovoltaic cell surface; the other side is a selective emitter surface.

In addition, the thermal performance is affected by the space between two surfaces if the space becomes on the order of the wavelength of the characteristic radiation (Boehm and Tien 1970, Whale and Cravalho 1997). However, in this study, the spacing is assumed to be large compared with the wavelength of the radiation, so the conventional radiative heat exchange analysis will be applied. Also, the spacing is assumed to be small compared with the size of the parallel-plate, so the edge effects will be neglected.

**Literature Survey**

The literature tends to focus on developments on either the PV cell side or the emitter side in the temperature range 1000 K to 2500 K. Although conclusions from this prior work are not directly related to thermal performance in the temperature range 350K to 550K, it is helpful to incorporate aspects of this previous work.
Wojtczuk et al. (1994) discussed $\text{In}_{x}\text{Ga}_{1-x}\text{As}$ thermophotovoltaic cell performance vs. bandgap. The power output of six compositions of indium gallium arsenide ($\text{In}_{x}\text{Ga}_{1-x}\text{As}$) cells with bandgaps of 0.74, 0.68, 0.64, 0.59, 0.55, and 0.5 eV were measured under a 1000 °C wide-band emitter. All the cell structures were identical, and the only difference was the bandgap of the cell emitter and base layers. The results showed that the 0.64 eV bandgap ($\text{In}_{0.62}\text{Ga}_{0.38}\text{As}$) cell had the highest power output. Additionally, the performance of 0.5 eV bandgap ($\text{In}_{0.79}\text{Ga}_{0.21}\text{As}$) cell fell short of the theoretical predictions under the relation of the maximum wavelength of spectral emissive power and the emissive temperature -- Wien’s Displacement Law. Theoretically, a 0.5 eV bandgap cell has a cutoff wavelength close to the optimum for a 1000 °C wide-band emitter.

Models of low-bandgap solar cells for thermophotovoltaic applications were set up by Jain and his colleagues (Jain et al. 1994). The modeling results showed that the $\text{InGaAs}$ cell (0.75 eV) efficiencies exceeding 30% were achievable for the Er-YAG selective emitter source at 1500 K when the cell’s series resistance was reduced. Modeling results predicted that optimized $\text{In}_{x}\text{Ga}_{1-x}\text{As}$ cells designed for TPV applications may lead to efficiencies in excess of 40%.

Wilt and Chubb (1997) reported on thermophotovoltaic energy conversion technology development at the NASA Lewis Research Center. They developed some kinds of thin film selective emitters fabricated from rare-earth yttrium aluminum garnets (YAG), such as Er-YAG (emission band at 1.55 μm) and Ho-YAG (emission band at
1.95 μm). These emitters have demonstrated in-band emittances of higher than 0.7 and out-of-band emittances of lower than 0.2 at 1500 K. Also, two rare earth elements can be added to the same emitter for increasing the emissive power density.

Gray and El-Husseini (1995) presented a paper discussing a parametric study of thermophotovoltaic system efficiency and output power density based on a simple model of the TPV system. The TPV system was modeled as an endoreversible thermodynamic engine. They used three cases to investigate the system efficiency and output power density in the temperature range 1500 K to 3000 K of the wide-band emitter (case 1: no spectral selection, case 2: spectral selection, high pass, and case 3: spectral selection, band pass). This study showed that the optimum TPV cell band gap depended not only on the emitter spectrum, but on the type and effectiveness of the spectral selection as well.

Adair and Rose (1995) discussed using selective emitters to increase thermophotovoltaic system efficiency. Theoretically and experimentally, they showed that selective emitters could improve the system efficiency of a TPV system by allowing the system to use less fuel per unit time than would be required for a wide-band emitter.

A study by Good, Chubb, and Lowe (1996) presented an optimization study of a selective emitter thermophotovoltaic system. They developed a computer model that incorporates detailed models of the individual system components; such as a model of the selective emitter component based on the approximation of a rare-earth selective emitter (Adair et al. 1994, Nelson, 1995, and Lowe et al. 1994), and a model of the PV...
cell component was the diode equation (Sze, 1985). The PV cell was characterized by a
bandgap energy and corresponding wavelength, the short-circuit current, the saturation
current, the series resistance, and the junction ideality factor. The model predicted the
component efficiencies, the overall system efficiency, and the system output power
density for variations in the emitter temperature, the spectral emissivity and emission
bandwidth of the emitter, the PV cell bandgap energy, the cell back-surface reflectivity,
and the long-wavelength emission band limit of the emitter.

A recent study by Fatemi et al. (1996) presented high efficiency converters for
thermophotovoltaic applications. TPV converters were built and tested under the
temperature 1700 K. In the emitter side, three different rare-earth-doped, single-crystal
YAG-based selective emitters and one wide-band emitter with a bandpass/infrared
reflector filter were used. YAG-based selective emitters were doped with 25% Ho, 30%
Tm, and 40% Er, and their emission peaks were 2.0 µm, 1.7 µm, and 1.5 µm
respectively. On the PV cell side, InGaAs/InP photovoltaic cells with bandgaps of 0.51
eV, 0.57 eV, and 0.69 eV were used. All three selective emitters and a wide-band
emitter were coupled to InGaAs/InP PV cells with bandgaps tuned to the emission
spectrum. The test data showed that the Er-YAG selective emitter with 0.69 eV PV cell
converter had the highest energy efficiency (approaching 30%), and the wide-band
emitter (with bandpass/infrared reflector filter) with 0.69 eV PV cell converter has the
highest electrical output power density near 2 W/cm².
CHAPTER 2

DESCRIPTION OF THE MODEL

The thermal analysis of an evacuated flat parallel-plate system consisting of a selective emitter and a photovoltaic material was investigated. In this study, the separation spacing was assumed to be large compared the wavelength of the radiation, but the separation spacing was assumed to be small compared with the size of the parallel-plate. The edge effects were neglected.

Generally, use of selective filters can improve the energy conversion efficiency in a TPV system (Vincente et al. 1996, Chen et al. 1996). In these cases, when the wavelength ranges of the radiation from the emitter side are out of the PV material bandgap energy ranges, some radiation is transmitted through the PV material, and some radiation is reflected back to the emitter surface where the energy is absorbed and re-emitted. This “recycling process” can get more desirable wavelength ranges from less valuable radiation to match the bandgap energy ranges of PV materials. However, the selective filter adds a degree of complexity of the TPV system construction and more cost. It is not a good idea to add a selective filter to such a low temperature TPV system. In this study, a selective filter was not considered in the model.
Photovoltaic Materials Considered

On the PV material side, there are four aspects related with the thermal analysis:

1. the types of the PV material; 2. the temperature of the PV material; 3. the spectral emissivity of the PV material; and 4. the antireflecting coating on the PV material.

1. The types of the PV material

From the literature survey, PV materials are usually the alloys from the III-V and IV families of semiconductors such as compounds of InGaAs, InSb, GaSb, GaInSb, SiGe, InAs, InAsP, InAlAs, GaAsSb, and Ge. These materials fall in the bandgap range between 1.1 eV to 0.36 eV, which offers many choices for the various wide-band and narrow-band emission sources for thermophotovoltaic applications (Jain et al. 1994).

Since high efficiency photovoltaic cells can be made of indium gallium arsenide (In\textsubscript{x}Ga\textsubscript{1-x}As), and the Indium “x” composition can be varied to change the bandgap range from GaAs (x = 0, 1.42 eV, 0.9 \textmu m cut off wavelength) to InAs (x = 1, 0.36 eV, 3.4 \textmu m cut off wavelength) to allow the PV cell bandgap to be spectrally matched to the General Purpose Heat Source (GPHS) to maximize electrical power output (Wojtczuk et al. 1994), compounds of In\textsubscript{x}Ga\textsubscript{1-x}As are more popularly used in the photovoltaic converters recently (Coutts et al. 1996).

In this study, based on the more mature development on indium gallium arsenide (In\textsubscript{x}Ga\textsubscript{1-x}As) for the PV cell side, three compounds of In\textsubscript{x}Ga\textsubscript{1-x}As were considered.

a. In(0.66)Ga(0.34)As (Bandgap energy = 0.61 eV)

b. In(0.72)Ga(0.28)As (Bandgap energy = 0.55 eV)

c. In(0.79)Ga(0.21)As (Bandgap energy = 0.49 eV)
2. The temperature of the PV material

From the characteristics of the III-V and IV families of semiconductors, the surface properties of semiconductors were almost constant near ambient temperature. In this study, the PV material was held at 300 K.

3. The spectral emissivity of the PV material

It is difficult to find the direct emissivities of the compounds of In(0.66)Ga(0.34)As, In(0.72)Ga(0.28)As, and In(0.79)Ga(0.21)As. In this study, the indirect method was used to estimate the emissivities of the In(0.66)Ga(0.34)As, In(0.72)Ga(0.28)As, and In(0.79)Ga(0.21)As.

First, from Handbook of Optical Constants of Solids (Palik, 1985), the spectral data of n_\lambda (index of refraction) and k_\lambda (extinction coefficient) for InAs and GaAs (see Appendix I) were found.

Second, using the Fresnel formula (Palik, 1985),

\[ \rho_\lambda = \frac{(n_\lambda - 1)^2 + k_\lambda^2}{(n_\lambda + 1)^2 + k_\lambda^2} \] (1)

the reflectivities (\rho_\lambda) for InAs and GaAs were calculated at each wavelength. The spectral absorptivity (\alpha_\lambda) was equal to (1.0 - \rho_\lambda) since InAs and GaAs were opaque. The absorptivities (\alpha_\lambda) for InAs and GaAs were calculated at each wavelength. According to the Kirchhoff's Law (Incropera and Dewitt, 1996), the absorptivity (\alpha_\lambda) is equal to the emissivity (\varepsilon_\lambda) at each wavelength. The emissivities (\varepsilon_\lambda) for InAs and GaAs were found at each wavelength.

Third, depending upon the composition of the PV materials, the emissivities (\varepsilon_\lambda) of three compounds of In_{1-x}Ga_{x}As were calculated at each wavelength using an
appropriate method.

Fourth, from the monochromatic emissivity ($\varepsilon$) data at each wavelength, the relationship between the emissivity ($\varepsilon_\lambda$) and wavelength ($\lambda$) at certain wavelength range was found for each of three compounds of the In$_{x_1}$Ga$_{1-x_1}$As using a least squares curvefit program (Culbreth, 1990). The relationships were as follows:

a. In(0.66)Ga(0.34)As (Bandgap energy = 0.61 eV), wavelength range from 0.2995 $\mu$m to 2.254 $\mu$m.

$$
\varepsilon_\lambda = 1.216186 - 3.720149 \lambda + 6.684274 \lambda^2 - 3.105558 \lambda^3 - 1.667874 \lambda^4 + 1.631244 \lambda^5 - 0.324471 \lambda^6
$$

(2)

b. In(0.72)Ga(0.28)As (Bandgap energy = 0.55 eV), wavelength range from 0.2995 $\mu$m to 2.48 $\mu$m.

$$
\varepsilon_\lambda = 1.474460 - 5.716184 \lambda + 12.590829 \lambda^2 - 11.606790 \lambda^3 + 4.594591 \lambda^4 - 0.653443 \lambda^5
$$

(3)

c. In(0.79)Ga(0.21)As (Bandgap energy = 0.49 eV), wavelength range from 0.2995 $\mu$m to 3.1 $\mu$m.

$$
\varepsilon_\lambda = 1.074011 - 3.158599 \lambda + 6.906868 \lambda^2 - 6.093030 \lambda^3 + 2.211407 \lambda^4 - 0.280348 \lambda^5
$$

(4)

4. The antireflecting coating on the PV material

From the literature survey, the PV material’s external quantum efficiency is defined as the ratio of the photogenerated carriers to the photon flux incident on the
photovoltaic (Block et al. 1992). An antireflecting coating on the PV material has a
major influence on the external quantum efficiency. So the external quantum efficiency
of the PV material with an antireflecting coating and external quantum efficiency of the
PV material without an antireflecting coating were considered in this study.

(1) External quantum efficiency over all wavelengths without an antireflecting coating on
the PV material

First, the data of the monochromatic external quantum efficiency over all
wavelengths without an antireflecting coating were estimated from the figure in Coutts's
paper (Coutts et al. 1996) (see Appendix II).

Second, using the least squares curvefit program (Culbreth 1990), the
relationship between the monochromatic external quantum efficiency and wavelength
over the entire spectrum was found for each of three types of In$_{x}$Ga$_{1-x}$As. The
relationships were as follows:

a. In(0.66)Ga(0.34)As (Bandgap energy = 0.61 eV), the wavelength range from 0.3 µm
to 2.1 µm.

\[ \eta_{\text{ex}} = -1.151838 + 5.479775 \lambda - 6.974839 \lambda^2 + 4.273858 \lambda^3 - 1.193912 \lambda^4 + 0.0974399 \lambda^5 \]  \hspace{1cm} (5)

b. In(0.72)Ga(0.28)As (Bandgap energy = 0.55 eV), the wavelength range from 0.3 µm
to 2.3 µm.
\[ \eta_{\text{fo}} = -1.068449 + 4.783940 \lambda - 4.997503 \lambda^2 + 1.843131 \lambda^3 + 0.173067 \lambda^4 - 0.238094 \lambda^5 + 0.030572 \lambda^6 \]  
\[ (6) \]

c. \text{In}(0.79)\text{Ga}(0.21)\text{As} (\text{Bandgap energy} = 0.49 \text{ eV}), \text{the wavelength range from} 0.3 \mu\text{m} \text{to} 2.5 \mu\text{m}.

\[ \eta_{\text{fo}} = -1.038761 + 4.576838 \lambda - 4.321949 \lambda^2 + 0.463098 \lambda^3 + 1.381295 \lambda^4 - 0.714228 \lambda^5 + 0.103018 \lambda^6 \]  
\[ (7) \]

(2) External quantum efficiency with an antireflecting coating on the PV material for a specific wavelength range

First, the data for the monochromatic external quantum efficiency with an antireflecting coating for a specific wavelength range were estimated from the figure in Wojtczuk's paper (Wojtczuk et al. 1994) (see Appendix II).

Second, using the least squares curvefit program (Culbreth 1990), the relationship between external quantum efficiency and wavelength at a specific range was found for each of three types of In\(_{x}\)Ga\(_{1-x}\)As. The relationships were as follows:

a. \text{In}(0.68)\text{Ga}(0.32)\text{As} (\text{Bandgap energy} = 0.59 \text{ eV}), \text{the wavelength range from} 1.0 \mu\text{m} \text{to} 1.8 \mu\text{m}.

\[ \eta_{\text{fo}} = (-13.993176 - 1.781044 \lambda - 26.657091 \lambda^2 + 23.162644 \lambda^3 - 5.546781 \lambda^4) \]  
\[ (8) \]

b. \text{In}(0.72)\text{Ga}(0.28)\text{As} (\text{Bandgap energy} = 0.55 \text{ eV}), \text{the wavelength range from} 1.0 \mu\text{m} \text{to} 1.8 \mu\text{m}.

\[ \eta_{\text{fo}} = -4.084742 + 8.393321 \lambda - 5.197048 \lambda^2 + 1.108136 \lambda^3 \]  
\[ (9) \]
c. In(0.79)Ga(0.21)As (Bandgap energy = 0.49 eV), the wavelength range from 1.0 μm to 1.8 μm.

\[ \eta = 1.414265 - 3.026149 \lambda + 2.365074 \lambda^2 - 0.568979 \lambda^3 \]  

(10)

**Selective Emitters Considered**

The energy radiated by a body is determined by the temperature of the body and its emissivity. In the selective emitter surface side, there are two aspects related to the thermal analysis: temperature of the selective emitter surface and emissivity of the selective emitter surface.

1. Temperature of the selective emitter surface

   Based upon the literature survey, the temperature of the selective emitter surface was taken to be around 1000 K to 2500 K in most of the previous studies of the TPV system.

   In this study, the application of the PV thermal system was based on much lower temperatures (around 200 K above ambient temperature). So the selective emitter surface temperature was taken to be in the range of 350 K to 550 K.

2. Emissivity of the selective emitter surface

   The emissivity of the selective emitter surface can vary a great deal by choosing a variety of emitter materials, coatings and other surface conditions. A high emissivity material emits radiation (photons) at a greater rate than a low emissivity material for the same surface temperature.

   In this study, the following three categories of emissivity were considered.
(1) Gray surface over all wavelengths ($\lambda = 0 \rightarrow \infty \text{\mu m}$)

Emissivity varying from 0.5 to 1.0.

(2) Step gray surface over entire PV materials' external quantum efficiency wavelength range.

Inside the PV materials' external quantum efficiency wavelength range, the emissivity was taken to vary from 0.5 to 1.0. Outside the PV materials' external quantum efficiency wavelength range, the emissivity was zero.

(3) Real selective emitter surface

Selective emission involves the use of certain materials that emit higher radiation in essentially a single narrow-band when heated and this higher radiation in a single narrow band can be matched to the wavelength range of the PV materials' external quantum efficiency. Electrical power output can only be produced within the wavelength range of the PV materials' external quantum efficiency. Outside of that range there is no power generation.

Because of rare-earth elements' unique electronic structure, these rare-earth elements emit in a narrow band when heated (Guazzoni et al. 1972, Adair and Rose, 1995). This is due to the fact that the 4f electron sub-orbital, which accounts for emission, lies inside the 5s and 5p electron orbitals. Therefore, the 5s and 5p electrons essentially shield the 4f emissions, yielding radiation characteristics of that for an isolated atom.
These narrow bands can be matched to the wavelength range of the PV materials' external quantum efficiency. Most of rare-earth elements used today are Erbium, Holmium, Neodymium, and Ytterbium in TPV systems.

Two kinds of single-crystal YAG-based thin film selective emitters doped with rare-earth elements were used in this study because their narrow emission bands were matched with the wavelength ranges of In(0.66)Ga(0.34)As, In(0.72)Ga(0.28)As, and In(0.79)Ga(0.21)As external quantum efficiency.

One is the 40% Er-1.5% Ho YAG (Yttrium Aluminum Garnet, Y₃Al₅O₁₂) thin film selective emitter. The following data were estimated from the figure in Lowe's paper (Lowe et al. 1994) (see Appendix III).

<table>
<thead>
<tr>
<th>Wavelength range λ</th>
<th>Emissivity ε (average value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3 μm - 1.4 μm</td>
<td>0.24</td>
</tr>
<tr>
<td>1.4 μm - 1.7 μm</td>
<td>0.62</td>
</tr>
<tr>
<td>1.7 μm - 3.2 μm</td>
<td>0.21</td>
</tr>
</tbody>
</table>

The other one is the 25% Ho YAG (Yttrium Aluminum Garnet, Y₃Al₅O₁₂) thin film selective emitter. The following data were estimated from the figure in Lowe's paper (Lowe et al. 1994) (see Appendix III).

<table>
<thead>
<tr>
<th>Wavelength range λ</th>
<th>Emissivity ε (average value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3 μm - 1.8 μm</td>
<td>0.20</td>
</tr>
</tbody>
</table>
1.8 μm - 2.1 μm 0.60
2.1 μm – 3.2 μm 0.20
CHAPTER 3

COMPUTATIONAL MODEL

The computational model was based on an evacuated parallel-plate system consisting of an emitter and a photovoltaic material with unit area surface. The spacing between the two surfaces was assumed to be large compared with the wavelength of the radiation, but it was assumed to be small compared with the size of the parallel-plate. The edge effects were neglected. Also, in the backside of the PV material is assumed to be perfectly insulated. Consider the configuration shown in Figure 1.

Figure 1 - Configuration of an evacuated parallel-plate system
Calculation Equations

According to the following calculation equations, the computational model was set up.

1. The relation between the photon energy and the wavelength (Iles, 1994)

\[ E = \frac{1.24}{\lambda} \quad (E \text{ in eV unit and } \lambda \text{ in } \mu m \text{ unit}) \]  \quad \text{(11)}

2. The relation between blackbody emissive power and emissive temperature — Stefan-Boltzmann Law (Incropera and Dewitt, 1996)

\[ E_a = \sigma T^4 \]  \quad \text{(12)}

3. The relation between the maximum wavelength of spectral emissive power and emissive temperature — Wien’s Displacement Law (Incropera and Dewitt, 1996)

\[ \lambda_{max} T = 2897.8 \quad \mu m \text{ K} \]  \quad \text{(13)}

4. Spectral black body emissive power — Planck Function (Incropera and Dewitt, 1996)

\[ E_{\lambda,b} = \frac{2 \cdot \pi \cdot h \cdot (c_0)^2}{\lambda^5 \cdot \left( \exp \left( \frac{h \cdot c_0}{\lambda \cdot k \cdot T} \right) - 1 \right)} \]  \quad \text{(14)}

5. Spectral emissive power in the selective emitter surface

\[ E_{\lambda,1} = e_{\lambda,1} \cdot E_{\lambda,b} \]  \quad \text{(15)}

6. Emissive power of the selective emitter surface for a certain wavelength range

\[ E_l = \int_{\lambda_1}^{\lambda_f} E_{\lambda,1} d\lambda \]  \quad \text{(16)}
7. Spectral net heat transfer between two surfaces (Incropera and Dewitt, 1996)

\[ q_\lambda = \frac{E_{\lambda,bl} - E_{\lambda,b2}}{\left( \frac{1}{e_{\lambda,1}} + \frac{1}{e_{\lambda,2}} - 1 \right)} \]  

(17)

8. Net heat transfer between two surfaces in a certain wavelength range

\[ q = \int_{\lambda_1}^{\lambda_f} q_\lambda \, d\lambda \]  

(18)

9. Spectral radiosity from a selective emitter surface

\[ q_{\lambda,oi} = E_{\lambda,bi} - \left( \frac{1 - e_{\lambda,1}}{e_{\lambda,1}} \right) q_\lambda \]  

(19)

10. Radiosity from a selective emitter surface in a certain wavelength range

\[ q_{oi} = \int_{\lambda_1}^{\lambda_f} q_{\lambda,oi} \, d\lambda \]  

(20)

11. Spectral power output between two surfaces

\[ P_\lambda = \eta_{\lambda,qu} q_{\lambda,oi} \]  

(21)

12. Power output between two surfaces in a certain wavelength range

\[ P = \int_{\lambda_1}^{\lambda_f} P_\lambda \, d\lambda \]  

(22)

13. Power generation efficiency

\[ \eta = \frac{P}{E_i} \quad \text{(P in W/m}^2\text{ unit and } E_i \text{ in W/m}^2\text{ unit)} \]  

(23)

**Model Description**

The computational model for an evacuated parallel-plate system consisting of an emitter and a photovoltaic PV material with unit area surface was written in a
FORTRAN 77 code. The Simpson's one-third rule for numerical integration was applied to the above integral equations (Jaluria, 1996). This program included one main part and five subroutine parts. The inputs included: initial wavelength of photons, final wavelength of photons, PV material temperature, selective emitter temperature, and selective emitter emissivity. The outputs included: net heat transfer, radiosity from emitter side, electrical power output, and power generation efficiency. Each compound of the In$_{x}$Ga$_{1-x}$As PV material had two programs. One was for the PV material with an antireflecting coating. The other one was for the PV material without an antireflecting coating. Thus, there were six total computational programs in this study.
CHAPTER 4

RESULTS AND DISCUSSION

Individual Results

The programs were all run using the same temperatures to insure an equal basis for discussion. A summary of these temperature values are as follows:

- PV material surface temperature = 300 K
- Selective emitter surface temperature varying from 350 K to 550 K

The results for the electrical power output and the power generation efficiency are illustrated here by using Quattro Pro 8 software.

PV Material 1 - In(0.79)Ga(0.21)As

In(0.79)Ga(0.21)As (Bandgap = 0.49 eV, $\lambda_{eq} = 0.3 \mu m - 2.5 \mu m$, without an antireflecting coating) PV material was coupled by each of the following four selective emitter surfaces individually (see Table 1).

1. Gray surface over all wavelengths ($\lambda = 0 \rightarrow \infty \mu m$, $\varepsilon$ varying from 0.5 to 1.0)

Figure 2 and Figure 3 illustrate the electrical power output and the power generation efficiency for a converter consisting of an In(0.79)Ga(0.21)As PV

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Table 1: Overview of figures for an In(0.79)Ga(0.21)As - 0.49 eV, no coating, emitter temperature from 350 K to 550 K.

<table>
<thead>
<tr>
<th>External Quantum Efficiency</th>
<th>Four Kinds of Emitter Surfaces</th>
<th>Figure No. for Power Generation Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gray Surface, Emissivity from 0.5 to 1.0</td>
<td>Figure #2</td>
<td>Figure #3</td>
</tr>
<tr>
<td>Step Gray Surface, Emissivity from 0.5 to 1.0</td>
<td>Figure #4</td>
<td>Figure #5</td>
</tr>
<tr>
<td>40% Er - 1.5% Ho YAG</td>
<td>Figure #6</td>
<td>Figure #7</td>
</tr>
<tr>
<td>25% Ho YAG</td>
<td>Figure #8</td>
<td>Figure #9</td>
</tr>
</tbody>
</table>

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material without an antireflecting coating and a emitter with a gray surface over all wavelengths.

\[ \text{In(0.79)Ga(0.21)Ga--0.49eV, No Coating} \]
\[ \text{All Wavelengths} \]

Figure 2 - Power output for a gray emitter surface over all wavelengths \((\lambda = 0 \rightarrow \infty \mu m)\)

\[ \text{In(0.79)Ga(0.21)As--0.49eV, No Coating} \]
\[ \text{All Wavelengths} \]

Figure 3 - Power generation efficiency for a gray emitter surface over all wavelengths \((\lambda = 0 \rightarrow \infty \mu m)\)
2. Step gray surface over the external quantum efficiency wavelength range of In(0.79)Ga(0.21)As PV material ($\lambda = 0 \rightarrow 0.3 \mu m$, $\varepsilon = 0.0$; $\lambda = 0.3 \mu m \rightarrow 2.5 \mu m$, $\varepsilon$ varying from 0.5 to 1.0; $\lambda = 2.5 \mu m \rightarrow \infty \mu m$, $\varepsilon = 0.0$).

Figure 4 shows the curves of the electrical power output versus the selective emitter temperature for a converter which consists of a step gray surface emitter and an In(0.79)Ga(0.21)As PV material without an antireflecting coating.

![In(0.79)Ga(0.21)As-0.49eV, No Coating]  
Wavelength Range 0.3-2.5 Micrometer

Figure 4 - Power output for a step gray emitter surface over the wavelength range of 0.3 $\mu$m to 2.5 $\mu$m.

Figure 5 shows the curves of the power generation efficiency versus the selective emitter temperature for a converter which consists of a step gray surface emitter and an In(0.79)Ga(0.21)As PV material without an antireflecting coating. The curves of the power generation efficiency in Figure 5 are almost parallel to each other in contrast to the curves in Figure 3 for the gray emitter surface over all wavelengths.
In(0.79)Ga(0.21)As—0.49eV, No Coating  
Wavelength Range 0.3-2.5 Micrometer

Figure 5 - Power generation efficiency for a step gray emitter surface over the wavelength range of 0.3 μm to 2.5 μm.

3. Real thin film selective emitter surface 1: 40% Er - 1.5% Ho YAG (λ = 0.3 → 1.4 μm, ε = 0.24; λ = 1.4 μm → 1.7 μm, ε = 0.62; λ = 1.7 μm → 2.5 μm, ε = 0.21).

Figure 6 plots the electrical power output as a function of the selective emitter’s temperature for a real converter. This is an In(0.79)Ga(0.21)As PV material without an antireflecting coating which is coupled with a 40% Er - 1.5% Ho YAG thin film selective emitter.

Figure 7 plots the power generation efficiency as a function of the selective emitter’s temperature for a real converter. In this case an In(0.79)Ga(0.21)As PV material without an antireflecting coating is coupled with a 40% Er - 1.5% Ho YAG thin film selective emitter.
In(0.79)Ga(0.21)--0.49eV, No Coating
Wavelength Range 0.3 - 2.5 Micrometer

Power Output (W/sq.m)

Temperature (K)

wavelength range  emissivity
0.3-1.4 micrometer  0.24
1.4-1.7 micrometer  0.62
1.7-2.5 micrometer  0.21

Figure 6 - Power output for a 40% Er- 1.5% Ho YAG thin film selective emitter surface.

In(0.79)Ga(0.21)As--0.49eV, No Coating
Wavelength Range 0.3 - 2.5 Micrometer

Efficiency

Temperature (K)

wavelength range  emissivity
0.3-1.4 micrometer  0.24
1.4-1.7 micrometer  0.62
1.7-2.5 micrometer  0.21

Figure 7 - Power generation efficiency output for a 40% Er - 1.5% Ho YAG thin film selective emitter surface.
4. Real thin film selective emitter surface 2: 25% Ho YAG ($\lambda = 0.3 \to 1.8 \, \mu m, \varepsilon = 0.20$;
$\lambda = 1.8 \, \mu m \to 2.1 \, \mu m, \varepsilon = 0.60$; $\lambda = 2.1 \, \mu m \to 2.5 \, \mu m, \varepsilon = 0.20$).

Figure 8 shows the electrical power output as a function of the selective emitter's
temperature for a real converter. Here an In(0.79)Ga(0.21)As PV material without an
antireflecting coating is coupled with a 25% Ho YAG thin film selective emitter. Using
the 25% Ho YAG thin film selective emitter generated more electrical power than using
the 40% Er - 1.5% Ho YAG thin film selective emitter.

In(0.79)Ga(0.21)As - 0.49eV, No Coating
Wavelength Range 0.3 - 2.5 Micrometer

Figure 8 - Power output for a 25% Ho YAG thin film selective

Figure 9 shows the power generation efficiency as a function of the selective
power emitter’s temperature for a real converter. This case considers that an
In(0.79)Ga(0.21)As PV material without an antireflecting coating Figure 9 shows the
generation efficiency as a function of the selective is coupled with a 25% Ho YAG thin
film selective emitter. Using the 25% Ho YAG thin film selective emitter results in a
higher power generation efficiency.
Figure 9 - Power generation efficiency output for a 25% Ho YAG thin film selective emitter surface.

PV Material 2 - In(0.72)Ga(0.28)As

In(0.72)Ga(0.28)As (Bandgap = 0.55 eV, $\lambda_{\text{em}} = 0.3 \mu m - 2.3 \mu m$, without an antireflecting coating) PV material was coupled by each of the following four selective emitter surfaces individually (see Table 2).

1. Gray surface over all wavelengths ($\lambda = 0 \rightarrow \infty \mu m$, $\varepsilon$ varying from 0.5 to 1.0)

Figure 10 and Figure 11 illustrate the electrical power output and the power generation efficiency for a converter consisting of an In(0.72)Ga(0.28)As PV material without an antireflecting coating and an emitter with a gray surface over all wavelengths.
Table 2: Overview of figures for an In(0.72)Ga(0.28)As - 0.55 eV, no coating, emitter temperature from 350 K to 550 K. emitter surface.

<table>
<thead>
<tr>
<th>External Quantum Efficiency</th>
<th>Four Kinds of Emitter Surfaces</th>
<th>Figure No. for Power Output</th>
<th>Figure No. for Power Generation Efficiency</th>
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</thead>
<tbody>
<tr>
<td>Gray Surface, Emissivity from 0.5 to 1.0</td>
<td>#10</td>
<td>#11</td>
<td></td>
</tr>
<tr>
<td>Step Gray Surface, Emissivity from 0.5 to 1.0</td>
<td>#12</td>
<td>#13</td>
<td></td>
</tr>
<tr>
<td>40% Er - 1.5% Ho YAG</td>
<td>#14</td>
<td>#15</td>
<td></td>
</tr>
<tr>
<td>25% Ho YAG</td>
<td>#16</td>
<td>#17</td>
<td></td>
</tr>
</tbody>
</table>
In(0.72)Ga(0.28)As–0.55eV, No Coating
All Wavelengths

Figure 10 - Power output for a gray emitter surface over all wavelengths ($\lambda = 0 \rightarrow \infty \mu m$)

In(0.72)Ga(0.28)As–0.55eV, No Coating
All Wavelengths

Figure 11 - Power generation efficiency for a gray emitter surface over all wavelengths ($\lambda = 0 \rightarrow \infty \mu m$)

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2. Step gray surface over the external quantum efficiency wavelength range of In(0.72)Ga(0.28)As PV material ($\lambda = 0 \rightarrow 0.3 \ \mu m$, $\varepsilon = 0.0$; $\lambda = 0.3 \ \mu m \rightarrow 2.3 \ \mu m$, $\varepsilon$ varying from 0.5 to 1.0; $\lambda = 2.3 \ \mu m \rightarrow \infty \ \mu m$, $\varepsilon = 0.0$).

Figure 12 shows the curves of electrical power output versus the selective emitter temperature for a converter which consists of a step gray surface emitter and an In(0.72)Ga(0.28)As PV material without an antireflecting coating.

![Figure 12](image)

Figure 12 - Power output for a step gray emitter surface over the wavelength range of 0.3 $\mu m$ to 2.3 $\mu m$.

Figure 13 shows the curves of the power generation efficiency versus the selective emitter temperature for a converter which consists of a step gray surface emitter and an In(0.72)Ga(0.28)As PV material without an antireflecting coating. The curves of the power generation efficiency in Figure 13 are almost parallel to each other in contrast to the curves in Figure 11 for the gray emitter surface over all wavelengths.
In(0.72)Ga(0.28)As—0.55eV, No Coating
Wavelength Range 0.3-2.3 Micrometer

Figure 13 - Power generation efficiency for a step gray emitter surface over the wavelength range of 0.3 μm to 2.3 μm.

3. Real thin film selective emitter surface 1: 40% Er - 1.5% Ho YAG (λ = 0.3 → 1.4 μm, ε = 0.24; λ = 1.4 μm → 1.7 μm, ε = 0.62; λ = 1.7 μm → 2.3 μm, ε = 0.21).

Figure 14 plots the electrical power output as a function of the selective emitter’s temperature for a real converter. Here an In(0.72)Ga(0.28)As PV material without an antireflecting coating is coupled with a 40% Er - 1.5% Ho YAG thin film selective emitter.

Figure 15 plots the power generation efficiency as a function of the selective emitter’s temperature for a real converter. This case considers that an In(0.72)Ga(0.28)As PV material without an antireflecting coating is coupled with a 40% Er - 1.5% Ho YAG thin film selective emitter.
Figure 14 - Power output for a 40% Er - 1.5% Ho YAG thin film selective emitter surface.

Figure 15 - Power generation efficiency for a 40% Er - 1.5% Ho YAG thin film selective emitter surface.
4. Real thin film selective emitter surface 2: 25% Ho YAG ($\lambda = 0.3 \rightarrow 1.8 \mu m, \varepsilon = 0.20$; $\lambda = 1.8 \mu m \rightarrow 2.1 \mu m, \varepsilon = 0.60$; $\lambda = 2.1 \mu m \rightarrow 2.3 \mu m, \varepsilon = 0.20$).

Figure 16 shows the variation of the electrical power output as a function of the selective emitter’s temperature for a real converter. Here it is considered that an In(0.72)Ga(0.28)As PV material without an antireflecting coating is coupled to a 25% Ho YAG thin film selective emitter. Using the 25% Ho YAG thin film selective emitter generates more electrical power than using the 40% Er - 1.5% Ho YAG thin film selective emitter.

Figure 16 - Power output for a 25% Ho YAG thin film selective emitter surface.

Figure 17 shows the variation of the power generation efficiency as a function of the selective emitter’s temperature for a real converter. Here an In(0.72)Ga(0.28)As PV material without an antireflecting coating is coupled with a 25% Ho YAG thin film selective emitter. The 25% Ho YAG thin film selective emitter shows a higher power
generation efficiency than others.

In(0.72)Ga(0.28)As – 0.55 eV, No Coating
Wavelength Range 0.3 - 2.3 Micrometer

![Graph showing efficiency vs temperature](image)

Figure 17 - Power generation efficiency for a 25% Ho YAG thin film selective emitter surface

PV Material 3 - In(0.66)Ga(0.34)As

In(0.66)Ga(0.34)As (Bandgap = 0.61 eV, \( \lambda_{\text{opt}} = 0.3 \mu m - 2.1 \mu m \), without an antireflecting coating) PV material was coupled to each of the following four selective emitter surfaces individually (see Table 3).

1. Gray surface over all wavelengths (\( \lambda = 0 \rightarrow \infty \mu m \), \( \varepsilon \) varying from 0.5 to 1.0)

Figure 18 and Figure 19 illustrate the electrical power output and the power generation efficiency for a converter consisting of an In(0.66)Ga(0.34)As PV material without an antireflecting coating and an emitter with a gray surface over all wavelengths.
Table 3: Overview of figures for an In(0.66)Ga(0.34)As - 0.61 eV, no coating, emitter temperature from 350 K to 550 K.

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<tbody>
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<td></td>
<td>Gray Surface, Emissivity from 0.5 to 1.0</td>
<td>#18</td>
<td>#19</td>
</tr>
<tr>
<td></td>
<td><img src="image1" alt="Graph 1" /></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Step Gray Surface, Emissivity from 0.5 to 1.0</td>
<td>#20</td>
<td>#21</td>
</tr>
<tr>
<td></td>
<td><img src="image2" alt="Graph 2" /></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>40% Er - 1.5% Ho YAG</td>
<td>#22</td>
<td>#23</td>
</tr>
<tr>
<td></td>
<td><img src="image3" alt="Graph 3" /></td>
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<tr>
<td></td>
<td>25% Ho YAG</td>
<td>#24</td>
<td>#25</td>
</tr>
<tr>
<td></td>
<td><img src="image4" alt="Graph 4" /></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 18 - Power output for a gray emitter surface over all wavelengths
($\lambda = 0 \rightarrow \infty \text{ } \mu m$)

Figure 19 - Power generation efficiency for a gray emitter surface over all wavelengths
($\lambda = 0 \rightarrow \infty \text{ } \mu m$)
2. Step gray surface over the external quantum efficiency wavelength range of
In(0.66)Ga(0.34)As PV material ($\lambda = 0 \rightarrow 0.3 \ \mu m$, $\varepsilon = 0.0$; $\lambda = 0.3 \ \mu m \rightarrow 2.1 \ \mu m$, $\varepsilon$ varying from 0.5 to 1.0; $\lambda = 2.1 \ \mu m \rightarrow \infty \ \mu m$, $\varepsilon = 0.0$).

Figure 20 shows the curves of electrical power output versus the selective emitter temperature for a converter which consists of a step gray surface emitter and an In(0.66)Ga(0.34)As PV material without an antireflecting coating.

![In(0.66)Ga(0.34)As--0.61eV, No Coating](Fig20)

Wavelength Range 0.3 - 2.1 Micrometer

Figure 20 - Power output for a step gray emitter surface over the wavelength range of 0.3 $\mu m$ to 2.1 $\mu m$.

Figure 21 shows the curves of the power generation efficiency versus the selective emitter temperature for a converter which consists of a step gray surface emitter and an In(0.66)Ga(0.34)As PV material without an antireflecting coating. The curves of the power generation efficiency in Figure 21 are almost parallel to each other in contrast to the curves in Figure 19 for the gray emitter surface over all wavelengths.

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Figure 21 - Power generation efficiency for a step gray emitter surface over the wavelength range of 0.3 \( \mu \text{m} \) to 2.1 \( \mu \text{m} \).

3. Real thin film selective emitter surface 1: 40\% Er - 1.5\% Ho YAG (\( \lambda = 0.3 \rightarrow 1.4 \) \( \mu \text{m} \), \( \varepsilon = 0.24 \); \( \lambda = 1.4 \mu \text{m} \rightarrow 1.7 \mu \text{m} \), \( \varepsilon = 0.62 \); \( \lambda = 1.7 \mu \text{m} \rightarrow 2.1 \mu \text{m} \), \( \varepsilon = 0.21 \)).

Figure 22 plots the electrical power output as a function of the selective emitter’s temperature for a real converter, where an \( \text{In}(0.66)\text{Ga}(0.34)\text{As} \) PV material without an antireflecting coating is coupled with a 40\% Er - 1.5\% Ho YAG thin film selective emitter.

Figure 23 plots the power generation efficiency as a function of the selective emitter’s temperature for a real converter. Here an \( \text{In}(0.66)\text{Ga}(0.34)\text{As} \) PV material without an antireflecting coating is coupled with a 40\% Er - 1.5\% Ho YAG thin film selective emitter.
Figure 22 - Power output for a 40% Er - 1.5% Ho YAG thin film selective emitter surface

Figure 23 - Power generation efficiency for a 40% Er - 1.5% Ho YAG thin film selective emitter surface
4. Real thin film selective emitter surface 2: 25% Ho YAG ($\lambda = 0 \rightarrow 1.8 \mu m, \varepsilon = 0.20$; $\lambda = 1.8 \mu m \rightarrow 2.1 \mu m, \varepsilon = 0.60$).

Figure 24 shows the variation of the electrical power output as a function of the selective emitter's temperature for a real converter, where an In(0.66)Ga(0.34)As PV material without an antireflecting coating is coupled with a 25% Ho YAG thin film selective emitter. Using the 25% Ho YAG thin film selective emitter generates more electrical power than using the 40% Er - 1.5% Ho YAG thin film selective emitter.

![Graph showing power output vs. temperature for In(0.66)Ga(0.34)As material without a coating, coupled with a 25% Ho YAG thin film selective emitter.](image)

**Figure 24 - Power output for a 25% Ho YAG thin film selective emitter surface**

Figure 25 shows the power generation efficiency as a function of the selective emitter's temperature for a real converter, where an In(0.66)Ga(0.34)As PV material without an antireflecting coating is coupled with a 25% Ho YAG thin film selective emitter. The 25% Ho YAG thin film selective emitter has a low power generation efficiency. It is different in contrast to the In(0.79)Ga(0.21)As and In(0.72)Ga(0.28)As.

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Antireflecting Coating Effect

An antireflecting (AR) coating on the PV materials influences the external quantum efficiency as mentioned before. The following figures show the effect of an AR coating on the electrical power output and the power generation efficiency.

The calculations were based on using the same selective emitter surface (a 40% Er - 1.5% Ho YAG thin film selective emitter) for the following three types of In$_{0.66}$Ga$_{0.34}$As PV materials with an antireflecting coating or without an antireflecting coating. Also, the specific wavelength range starting at 1.0 μm and ending at 1.8 μm was used for the calculations (see Table 4).
Table 4: Summary of figures for a 40% Er - 1.5% Ho YAG thin film selective emitter surface with the emitter temperature from 350 K to 550 K, external quantum efficiency wavelength range 1.0 μm - 1.8 μm

<table>
<thead>
<tr>
<th>40% Er - 1.5% Ho YAG Emissivity</th>
<th>Three Kinds of EQE of In$_{1-x}$Ga$_x$As With or Without an Antireflecting Coating</th>
<th>Figure No. for Power Output</th>
<th>Figure No. for Power Generation Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>In$<em>{0.6}$Ga$</em>{0.4}$As - 0.49 eV, no coating</td>
<td>#26</td>
<td>#27</td>
<td></td>
</tr>
<tr>
<td>In$<em>{0.6}$Ga$</em>{0.4}$As - 0.49 eV, coating</td>
<td>#26</td>
<td>#27</td>
<td></td>
</tr>
<tr>
<td>In$<em>{0.7}$Ga$</em>{0.3}$As - 0.55 eV, no coating</td>
<td>#28</td>
<td>#29</td>
<td></td>
</tr>
<tr>
<td>In$<em>{0.7}$Ga$</em>{0.3}$As - 0.55 eV, coating</td>
<td>#28</td>
<td>#29</td>
<td></td>
</tr>
<tr>
<td>In$<em>{0.6}$Ga$</em>{0.4}$As - 0.61 eV, no coating</td>
<td>#30</td>
<td>#31</td>
<td></td>
</tr>
<tr>
<td>In$<em>{0.6}$Ga$</em>{0.4}$As - 0.59 eV, coating</td>
<td>#30</td>
<td>#31</td>
<td></td>
</tr>
</tbody>
</table>
1. PV material 1 - In(0.79)Ga(0.21)As with an antireflecting coating or without an antireflecting coating.

Figure 26 plots two curves of the electrical power output versus the selective emitter temperature for a converter which consists of a 40% Er - 1.5% Ho YAG thin film selective emitter and an In(0.79)Ga(0.21)As PV material with an antireflecting coating or without an antireflecting coating. The results show that using an In(0.79)Ga(0.21)As PV material without an antireflecting coating could generate more electrical power.

![Graph](image)

Figure 26 - Power output for a 40% Er - 1.5% Ho YAG thin film selective emitter surface and an In(0.79)Ga(0.21)As PV material

Figure 27 shows two curves of the power generation efficiency versus the selective emitter temperature for a converter consisting of a 40% Er - 1.5% Ho YAG thin film selective emitter and an In(0.79)Ga(0.21)As PV material. One curve represents the presence of an antireflecting coating; this is not present in the other. The results
show that using an In(0.79)Ga(0.21)As PV material without an antireflecting coating is efficient.

![Graph showing power generation efficiency](image)

**In(0.79)Ga(0.21)As - 0.49 eV**
Wavelength Range 1.0-1.8 Micrometer

Figure 27 - Power generation efficiency for a 40% Er - 1.5% Ho YAG thin film selective emitter surface and an In(0.79)Ga(0.21)As PV material

2. PV material 2 - In(0.72)Ga(0.28)As with an antireflecting coating or without an antireflecting coating.

Figure 28 and Figure 29 show the variation of the electrical power output and power generation efficiency versus the selective emitter temperature for a converter which consists of a 40% Er - 1.5% Ho YAG thin film selective emitter and an In(0.72)Ga(0.28)As PV material. Each figure has two curves. One curve includes the effect of an antireflecting coating; the other one does not. The results show that using an In(0.72)Ga(0.28)As PV material with an antireflecting coating generates more power and has a higher efficiency. The results are different from Figure 26 and Figure 27.
Figure 28 - Power output for a 40% Er - 1.5% Ho YAG thin film selective emitter surface and an In(0.72)Ga(0.28)As PV material.

Figure 29 - Power generation efficiency for a 40% Er - 1.5% Ho YAG thin film selective emitter surface and an In(0.72)Ga(0.28)As PV material.
3. PV material 3 - In(0.66)Ga(0.34)As with an antireflecting coating or without an antireflecting coating.

Figure 30 illustrates the relation between the electrical power output and the selective emitter temperature for a converter which consists of a 40% Er- 1.5% Ho YAG thin film selective emitter and an In(0.66)Ga(0.34)As PV material with an antireflecting coating or without an antireflecting coating. Similar results are shown in Figure 28. Using an In(0.66)Ga(0.34)As PV material with an antireflecting coating generates more electrical power than that without an antireflecting coating.

![Graph showing power output vs. temperature](image)

Figure 30 - Power output for a 40% Er - 1.5% Ho YAG thin film selective emitter surface and an In(0.66)Ga(0.34)As PV material.

Figure 31 shows how power generation efficiency varies with the selective emitter temperature for a converter consisting of a 40% Er- 1.5% Ho YAG thin film selective emitter and an In(0.66)Ga(0.34)As PV material with and without an AR
coating. These results are similar to those shown in Figure 29. Using an

\[ \text{In(0.66)Ga(0.34)As} \] PV material with an antireflecting coating is more efficient than that
without an antireflecting coating.

\[ \text{In(0.66)Ga(0.34)As} - 0.61 \text{ eV} \]

Wavelength Range 1.0-1.8 Micrometer

![Graph showing power generation efficiency for a 40% Er - 1.5% Ho YAG thin film selective emitter surface and an In(0.66)Ga(0.34)As PV material.]

Figure 31 - Power generation efficiency for a 40% Er - 1.5% Ho YAG thin film selective emitter surface and an In(0.66)Ga(0.34)As PV material.

Comparison

The comparison section is divided into two parts. The first part is about the
electrical power output. The second part deals with the power generation efficiency.
The comparison is based on the individual results shown earlier.

Comparison of Electrical Power Output Results

Comparison for electrical power output includes five aspects: 1. emissivity of the
selective emitter; 2. temperature of the selective emitter; 3. emission surfaces of the selective
emitters; 4. types of the PV materials; and 5. antireflecting coating of the PV material.
1. Emissivity of the selective emitter

Figures 32a and 32b show three curves of the electrical power output versus the emissivity of the step gray emitter surface over the external quantum efficiency of the PV materials' wavelength range at emitter temperature 350 K and 550 K. These curves indicate that the electrical power output increases with the increasing emissivity of the selective emitter.

![Step Gray Emitter Surface](image)

**Figure 32a** - Comparison of electrical power output for a step gray emitter surface over the external quantum efficiency of the PV materials' wavelength range at an emitter temperature of 350 K.

Additionally, the results show that the curve for In(0.79)Ga(0.21)As has the highest ratio of $\delta P / \delta \epsilon$ and the highest electrical power output at each value of emissivity ($\epsilon$) even with the lowest value of external quantum efficiency. One reason for this is that In(0.79)Ga(0.21)As has a wider wavelength range of external quantum efficiency ($\lambda = \ldots$)
0.3 μm to 2.5 μm) than In(0.72)Ga(0.28)As and In(0.66)Ga(0.34)As. Another reason is that the wavelength range of external quantum efficiency is closer to the wavelength of the maximum emissive power (according to the Wien’s Displacement Law, λ around 5.0 μm (550 K) to 8.0 μm (350 K)) than In(0.72)Ga(0.28)As and In(0.66)Ga(0.34)As.

Figure 32b - Comparison of electrical power output for a step gray emitter surface over the external quantum efficiency of the PV materials’ wavelength range at an emitter temperature of 550 K.

2. Temperature of the selective emitter

Figures 33a and 33b show how the electrical power output increases the emissive temperature with the step gray emitter surface over the external quantum efficiency of the PV materials’ wavelength range at emissivity 0.5 and 1.0. Each figure includes three curves, one each for In(0.79)Ga(0.21)As, In(0.72)Ga(0.28)As, and In(0.66)Ga(0.34)As.
Figure 33a - Comparison of electrical power output for a step gray emitter surface over the external quantum efficiency of the PV materials' wavelength range with emitter emissivity = 0.5.

Figure 33b - Comparison of electrical power output for a step gray emitter surface over the external quantum efficiency of the PV materials' wavelength range with emitter emissivity = 1.0.
The plots show that the curve for In(0.79)Ga(0.21)As has the highest electrical power output at each value of the emissive temperature even with the lowest value of external quantum efficiency. This is because In(0.79)Ga(0.21)As has a wider wavelength range of external quantum efficiency (\( \lambda = 0.3 \, \mu m \) to 2.5 \( \mu m \)) than In(0.72)Ga(0.28)As and In(0.66)Ga(0.34)As. Also the wavelength range of external quantum efficiency is closer to the wavelength of the maximum emissive power (according to the Wien’s Displacement Law, \( \lambda_{\text{max}} \) around 5.0 \( \mu m \) (550 K) to 8.0 \( \mu m \) (350 K)) than In(0.72)Ga(0.28)As and In(0.66)Ga(0.34)As. Furthermore, Figures 33a and 33b show the electrical power output dramatically increases with increasing emissive temperature. This is due to the fact that the emissive power increases with the fourth power of the emissive temperature. Obviously, using a high emissive temperature produces more electrical power than using a low emissive temperature. Finally, in comparing both figures, the conclusion is that using a high emissivity of a selective emitter could generate more electrical power. However, the power increase is not as dramatic as that resulting from temperature increases.

3. Emission surfaces of the selective emitters

The curves in Figure 34 show the electrical power output comparison for four kinds of the emitter surfaces. The results show that electrical power output in a system with a gray surface over whole wavelengths (\( \lambda = 0 \rightarrow \infty \, \mu m \)) is the same as in a step gray surface over PV materials’ external quantum efficiency wavelength range. The reason is that the wavelength range of the emissivity in both gray surfaces exactly
matches the wavelength range of the PV material's external quantum efficiency. In addition, the plots show that using real rare-earth thin film selective emitter surfaces generates less electrical power than using gray surfaces. This is because the wavelength range of high emissivity is narrow in the real rare-earth thin film selective emitter surfaces. Meanwhile, the value of electrical power output with the 25% Ho YAG selective emitter surface is higher than with the 40% Er - 1.5% Ho YAG selective emitter surface because the wavelength range of high emissivity is more matchable to the wavelength range of the PV material's external quantum efficiency peak.

Figure 34 - Comparison of electrical power output for four kinds of emitter surfaces

4. Types of the PV materials

According to Figures 32a, 32b, 33a, 33b, and previous figures in the results section, the results show that using In(0.79)Ga(0.21)As PV material generates highest electrical power output, and using In(0.66)Ga(0.34)As PV material generates lowest
electrical power output. The reason for this is that In(0.79)Ga(0.21)As PV material has the widest wavelength range of external quantum efficiency (\(\lambda = 0.3 \, \mu m \) to \(2.5 \, \mu m\)) among others. Also the wavelength range of external quantum efficiency is closer to the wavelength of the maximum emissive power (according to Wien's Displacement Law, \(\lambda_{\text{max}}\) around 5.0 \(\mu m\) (550 K) to 8.0 \(\mu m\) (350 K)) than In(0.72)Ga(0.28)As and In(0.66)Ga(0.34)As.

5. Antireflecting coating of the PV material.

In comparing Figures 26, 28, and 30 in the results section, the conclusion is that using an antireflecting coating can improve the electrical power output of the system, but it is not always the case depending on the certain wavelength range. It is like a tuned circuit, which responds best within a limited wavelength range. In this study, in the wavelength range 1.0 \(\mu m\) - 1.8 \(\mu m\), the electrical power output increases with an antireflecting coating used on In(0.72)Ga(0.28)As PV material and In(0.66)Ga(0.34)As PV material (see Figure 28 and 30). However, electrical power output decreases when an antireflecting coating is used on In(0.79)Ga(0.21)As PV material (see Figure 26).

Comparison of Power Generation Efficiency Results

Comparisons of power generation efficiency results includes five aspects: 1. emissivity of the selective emitter; 2. temperature of the selective emitter; 3. emission surfaces of the selective emitters; 4. types of the PV materials; and 5. effect of antireflecting coating on the PV material.
Figure 35a - Comparison of power generation efficiency for a step gray emitter surface over the external quantum efficiency of the PV materials' wavelength range at an emitter temperature of 350 K.

Figure 35b - Comparison of power generation efficiency for a step gray emitter surface over the external quantum efficiency of the PV materials' wavelength range at an emitter temperature of 550 K.
1. Emissivity of the selective emitter.

Figures 35a and 35b show three curves of the power generation efficiency versus the emissivity of the step gray emitter surface over the external quantum efficiency of the PV materials' wavelength range, at all emitter temperatures of 350 K and 550 K. The three curves indicate that the power generation efficiency decreases with increasing emissivity of the selective emitter. The reason for this is that the electrical power output increases in the numerator more slowly than the emissivity of the selective emitter increases in the denominator, with the black body emissive power remaining constant. Furthermore, both figures show that the curve for In(0.72)Ga(0.28)As has the highest power generation efficiency at each value of emissivity (ε). The reason for this is that In(0.72)Ga(0.28)As has a higher value of the external quantum efficiency than others.

2. Temperature of the selective emitter

Figures 36a and 36b show the power generation efficiency versus the emissive temperature with a step gray emitter surface coinciding with the external quantum efficiency of the PV materials' wavelength range at emissivity 0.5 and 1.0. Each figure includes three curves for In(0.79)Ga(0.21)As, In(0.72)Ga(0.28)As, and In(0.66)Ga(0.34)As. Three curves indicate that the power generation efficiency increases with increasing emissive temperature. Both figures show that the curve for In(0.72)Ga(0.28)As has the highest power generation efficiency at each value of the emissive temperature. The reason for this is that In(0.72)Ga(0.28)As has the higher value of the external quantum efficiency than others.
Figure 36a - Comparison of power generation efficiency for a step gray emitter surface over the external quantum efficiency of PV materials' wavelength range at emissivity = 0.5

Figure 36b - Comparison of power generation efficiency for a step gray emitter surface over the external quantum efficiency of PV materials' wavelength range at emissivity = 1.0
3. Emission surfaces of the selective emitters

The curves in Figure 37 show the power generation efficiency comparison for four kinds of emitter surfaces. The results show that power generation efficiency with a gray surface over whole wavelengths ($\lambda = 0 \rightarrow \infty \mu m$) has the lowest value (near zero). On the other hand, the power generation efficiency for a 25% Ho YAG thin film selective emitter surface has the highest value (between 0.23 to 0.28, depending on the emissive temperature). The reason for this is that electrical power output can only be generated inside the wavelength range of the PV material external quantum efficiency. There is no electrical power output outside the wavelength range of the PV material external quantum efficiency no matter how strong the emissive power is. The value of electrical power output with the 25% Ho YAG selective emitter surface is higher than that with the 40% Er - 1.5% Ho YAG selective emitter surface because the wavelength range of high emissivity is more matchable to the wavelength range of the PV material's external quantum efficiency peak.

In comparing Figure 34 and Figure 37, the results show that a selective emitter surface with the highest electrical power output is the same as a selective emitter surface with the highest power generation efficiency. This is because the wavelength range of high emissivity is narrow for the real rare-earth thin film selective emitter surfaces, and this is close to the wavelength range of the PV material external quantum efficiency's peak. Thus, using a 25% Ho YAG thin film selective emitter surface is more efficient than using others.
4. Types of the PV materials

According to the Figures 35a, 35b, 36a, 36b, and other figures in the results section, it can be concluded that using In(0.72)Ga(0.28)As PV material is more efficient than either In(0.79)Ga(0.21)As PV material or In(0.66)Ga(0.34)As PV material. The reason for this is that In(0.72)Ga(0.28)As PV material has a higher peak value of external quantum efficiency ($\eta_{eq} = 0.52$) than In(0.79)Ga(0.21)As PV material ($\eta_{eq} = 0.43$). Also the wavelength range ($\lambda = 0.3 \ \mu m - 2.3 \ \mu m$) of the external quantum efficiency is closer to the wavelength of the maximum emissive power (according to Wien's Displacement Law, $\lambda_{max}$ around 5.0 $\mu m$ (550 K) to 8.0 $\mu m$ (350 K)) than that for In(0.66)Ga(0.34)As ($\lambda = 0.3 \ \mu m - 2.1 \ \mu m$).

In comparing Figures 32a, 32b, 33a, and 33b as well as Figures 35a, 35b, 36a,
and 36b, these results show that a PV material with the highest electrical power output is not the same as a PV material with the highest power generation efficiency.

5. Effect of antireflecting coating on the PV material.

In comparing Figures 27, 29, and 31, the conclusion can be drawn that using an antireflecting coating on the PV material could improve the power generation efficiency, but it is not always the case (this depends on the wavelength range). It is like a tuned circuit, which responds best within a limited wavelength range. In this study, in the wavelength range 1.0 μm - 1.8 μm, the power generation efficiency increases with an antireflecting coating used on In(0.72)Ga(0.28)As PV material and In(0.66)Ga(0.34)As PV material (see Figures 29 and 31). However, the electrical power output decreases when an antireflecting coating is used on In(0.79)Ga(0.21)As PV material (see Figure 27).

Discussion

From the above individual results section and comparison section, the following comparative statements can be made:

- Using a PV material with a higher external quantum efficiency, more electrical power can be generated, and the power generation efficiency is higher.

- Using a PV material with a lower bandgap photon energy (longer wavelength) within the limited bandgap energy range, more electrical power could be generated, and the power generation efficiency is higher.

- Using a PV material with a wider wavelength range of external quantum
efficiency, more electrical power can be generated.

- Using a selective emitter surface with a higher emissivity, more electrical power can be generated.

- Using a selective emitter surface with a higher emissive temperature, more electrical power can be generated, and the power generation efficiency is higher.

In this study, the results show that the amount of electrical power output is small, from $9.85 \times 10^9$ W/sq.m to 4.70 W/sq.m (depending on the emissive temperature, emissivity, PV material, and emitter surface). The electrical power output level could be increased significantly if PV materials with external quantum efficiency peaks between 5 μm and 8 μm could be developed. However, the results are applicable if scientists make a breakthrough in the development of PV materials and emitters in the emissive temperature starting above the ambient temperature. What are the potential maximum electrical power output and power generation efficiency in the temperature range of 350 K to 550 K from the radiative heat transfer point of view? The following cases deal with the above question.

Case 1: More Realistic

In order to calculate this more realistic case, the following conditions are assumed:

1. The width of the wavelength range of the PV material external quantum efficiency is 2.2 μm based on the external quantum efficiency of the $\text{In}_x\text{Ga}_{1-x}\text{As}$ PV material.
2. The value of the PV material external quantum efficiency over the wavelength range is 0.8 based on In$_{0.5}$Ga$_{0.5}$As PV material with an antireflecting coating.

3. The emitter surface is a step gray emitter surface over the external quantum efficiency wavelength range, and the emissivity is equal to 1.0.

4. The external quantum efficiency wavelength starts at 0.3 μm and ends at the 2.5 μm based on In$_{0.5}$Ga$_{0.5}$As PV material.

The calculation results show that the maximum electrical power output is between 0.027 W/sq.m and 18.736 W/sq.m according to the emissive temperature, and the power generation efficiency is 0.80 (see Table 5, and Figures 38 and 39).

Table 5: Case 1 for a PV material external quantum efficiency wavelength range between 0.3 μm and 2.5 μm

<table>
<thead>
<tr>
<th>Emitter Temperature (K)</th>
<th>Beginning Wavelength (μm)</th>
<th>Ending Wavelength (μm)</th>
<th>Max. Power Output (W/sq.m)</th>
<th>Power Generation Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>0.3</td>
<td>2.5</td>
<td>0.027</td>
<td>0.8</td>
</tr>
<tr>
<td>370</td>
<td>0.3</td>
<td>2.5</td>
<td>0.07</td>
<td>0.8</td>
</tr>
<tr>
<td>390</td>
<td>0.3</td>
<td>2.5</td>
<td>0.167</td>
<td>0.8</td>
</tr>
<tr>
<td>410</td>
<td>0.3</td>
<td>2.5</td>
<td>0.362</td>
<td>0.8</td>
</tr>
<tr>
<td>430</td>
<td>0.3</td>
<td>2.5</td>
<td>0.739</td>
<td>0.8</td>
</tr>
<tr>
<td>450</td>
<td>0.3</td>
<td>2.5</td>
<td>1.418</td>
<td>0.8</td>
</tr>
<tr>
<td>470</td>
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<td>2.5</td>
<td>2.579</td>
<td>0.8</td>
</tr>
<tr>
<td>490</td>
<td>0.3</td>
<td>2.5</td>
<td>4.48</td>
<td>0.8</td>
</tr>
<tr>
<td>510</td>
<td>0.3</td>
<td>2.5</td>
<td>7.482</td>
<td>0.8</td>
</tr>
<tr>
<td>530</td>
<td>0.3</td>
<td>2.5</td>
<td>12.016</td>
<td>0.8</td>
</tr>
<tr>
<td>550</td>
<td>0.3</td>
<td>2.5</td>
<td>18.736</td>
<td>0.8</td>
</tr>
</tbody>
</table>
Case 2: More Ideal

In order to calculate this more ideal case, the following conditions are assumed:

1. The width of the wavelength range of the PV material external quantum efficiency is 2.2 μm based on the external quantum efficiency of the In₀.₅Ga₀.₅As PV material.

2. The value of the PV material external quantum efficiency over the wavelength range is 0.8 based on In₀.₅Ga₀.₅As PV material with an antireflecting coating.

3. The emitter surface is a step gray emitter surface over the external quantum efficiency wavelength range, and the emissivity is equal to 1.0.

4. The wavelength range of the PV material external quantum efficiency matches the peak of black body emissive power distribution, depending on the emissive temperature - Wien’s Displacement Law (Incropera and Dewitt, 1996).

Table 6: Case 2 for a PV material external quantum efficiency wavelength range match with the wavelength range of the black body emissive power peak

<table>
<thead>
<tr>
<th>Emitter Temperature (K)</th>
<th>Beginning Wavelength (μm)</th>
<th>Ending Wavelength (μm)</th>
<th>Max. Power Output (W/sq.m)</th>
<th>Power Generation Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>7.179</td>
<td>9.379</td>
<td>78.08</td>
<td>0.8</td>
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<td>103.28</td>
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<tr>
<td>390</td>
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<td>8.53</td>
<td>156.99</td>
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</tr>
<tr>
<td>410</td>
<td>5.968</td>
<td>8.168</td>
<td>171.36</td>
<td>0.8</td>
</tr>
<tr>
<td>430</td>
<td>5.639</td>
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<td>217.21</td>
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<tr>
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<td>5.338</td>
<td>7.538</td>
<td>272.26</td>
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<tr>
<td>470</td>
<td>5.066</td>
<td>7.266</td>
<td>337.31</td>
<td>0.8</td>
</tr>
<tr>
<td>490</td>
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<td>7.014</td>
<td>414.97</td>
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<td>6.782</td>
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<td>530</td>
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<td>6.568</td>
<td>610.25</td>
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<td>550</td>
<td>4.169</td>
<td>6.369</td>
<td>732.49</td>
<td>0.8</td>
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</table>
The calculation results show that the maximum electrical power output is between 78.08 W/m² and 732.49 W/m² according to the emissive temperature, and the power generation efficiency is 0.80 (see Table 6, and Figures 38 and 39).

From above two cases, the results show that shifting a PV material external quantum efficiency wavelength range close to the wavelength range of a black body emissive power peak is very important. It can dramatically increase the electrical power generated, even at the low emissive temperature range. Finding a PV material with long wavelength and high external quantum efficiency as well as a selective emitter with high emissivity is a key job in the low emissive temperature range TPV system. The results will help find the directions for improvement of electrical power output.

**Figure 38** - Maximum electrical power output for two cases at emissivity = 1.0
Figure 39 - Power generation efficiency for two cases at emissivity = 1.0

Case 3: Closely - Spaced Surfaces

In this study, the spacing is assumed to be large compared to the wavelength of the radiation. The Planck function for the spectral emissive power of a blackbody and the Stefan - Boltzmann Radiation Law are used to integrate the spectral emissive power over all wavelengths.

If the spacing between the two surfaces is on the order of the wavelength of the radiation, it has been established that the radiation heat exchange will be greatly enhanced (Boehm and Tien, 1970, Whale and Cravalho, 1997). The enhancement could be several orders of magnitude (see Appendix IV). This could, in turn, greatly enhance the electrical power generation capabilities of a TPV system. Techniques of analysis are quite involved, but merit application in future work.
Case 4: Carnot Cycle

From the thermodynamic point of view, a TPV system looks like a special case of an irreversible thermodynamics engine operation between two temperatures. The emitter side is maintained at a constant temperature of \( T_1 \) by a heat transfer, from a primary heat source, where the PV material side is maintained at a temperature of \( T_2 \) by another heat transfer. If all the interactions between two sides were reversible, the Carnot cycle could be applied to predict the maximum possible thermal efficiency. The Carnot cycle thermal efficiency (Pitzer, 1995) is given by:

\[
\eta = 1 - \frac{T_2}{T_1}
\]

(24)

Table 7: Values of the Carnot cycle efficiency and the power generation efficiency

<table>
<thead>
<tr>
<th>Emissive Temperature ( T_1 ) (K)</th>
<th>PV Material Temperature ( T_2 ) (K)</th>
<th>Carnot Efficiency ( \eta_c )</th>
<th>Power Generation Efficiency ( \eta ) (a 25% Ho YAG Emitter and an In(0.72)Ga(0.28)As)</th>
<th>Power Generation Efficiency ( \eta ) (a Step Gray Emitter and an In(0.72)Ga(0.28)As)</th>
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</thead>
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<tr>
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<tr>
<td>430</td>
<td>300</td>
<td>0.3023</td>
<td>0.3061</td>
<td>0.199</td>
</tr>
<tr>
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<td>300</td>
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<td>0.3119</td>
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</tr>
<tr>
<td>470</td>
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<td>0.3187</td>
<td>0.212</td>
</tr>
<tr>
<td>490</td>
<td>300</td>
<td>0.3878</td>
<td>0.3253</td>
<td>0.219</td>
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<tr>
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<td>0.4118</td>
<td>0.3319</td>
<td>0.226</td>
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<td>300</td>
<td>0.434</td>
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</tr>
<tr>
<td>550</td>
<td>300</td>
<td>0.4545</td>
<td>0.3449</td>
<td>0.238</td>
</tr>
</tbody>
</table>

Table 7 and Figure 40 show the values of the Carnot cycle efficiency and the power generation efficiency at an emitter temperature range of 350 K to 550 K. The data shows that the power generation efficiency is higher than the Carnot cycle efficiency in the temperature range of 350 K to 430 K. There are three possible reasons to cause this trouble, which gives the power generation efficiency that is higher than the Carnot.

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Figure 40 - Curves of the power generation efficiency and the Carnot cycle efficiency. The model is assumed to be perfect insulated on the backside of the PV material. Nearly all radiosity from the emitter side to the PV material is converted into the electrical power. It is slightly different from the model of the Carnot engine. The second reason here is that the emissive power is used in the denominator of the formula's power generation efficiency. Actually, the electrical power is converted from the radiosity. The last reason here is that the temperature in the PV material side is assumed to be constant.
CHAPTER 5

CONCLUSION

This study examined the thermal analysis of an evacuated parallel-plate system consisting of a selective emitter and a photovoltaic (PV) material with the emissive temperatures ranging from 350 K to 550 K. Three types of indium gallium and arsenide (In$_{a}$Ga$_{1-a}$As) and four kinds of emitters were considered. Along with the appropriate equations, computer models generated the electrical power output and power generation efficiency for each individual system. The results were then compared to each other to give insight into the interrelationship between the selective surface properties and the photovoltaic (PV) characteristics, and the appropriate ideal cases with the maximum electrical power output and power generation efficiency were discussed.

On the photovoltaic (PV) material side, using indium gallium and arsenide (In(0.79)Ga(0.21)As) PV material with an external quantum efficiency wavelength range between 0.3 μm and 2.5 μm produces more electrical power than others. However, using indium gallium and arsenide (In(0.72)Ga(0.28)As) PV material with an external quantum efficiency wavelength range between 0.3 μm and 2.3 μm has the highest power generation efficiency. The antireflecting coating can have a major effect on improving
wavelength range of the external quantum efficiency and the PV material.

On the emitter side, using a gray emitter surface over all wavelengths or a step gray emitter surface over the PV materials’ external quantum efficiency wavelength range generates more electrical power output than others. The surface doped with rare-earth elements thin film selective emitters has higher power generation efficiencies than do the gray surface of the emitters. The single-crystal Yttrium-Aluminum-Garnet-Based \((Y_3Al_5O_{12})\) thin film selective emitter doped with 25% Holmium rare-earth element (25% Ho YAG) has the highest power generation efficiency among the four emitters.

Based upon the possible technological development in the thermophotovoltaic (TPV) system between emissive temperatures of 1000 K and 2500 K, a better choice for a TPV system between the emissive temperature 350 K and 550 K is found from this study. The choice is using \(\text{In}(0.72)\text{Ga}(0.28)\text{As}\) with an antireflecting coating on the PV material side and using the 25% Ho YAG thin film selective emitter on the emitter side, and keeping the emissive temperature as high as better. The power generation efficiency can reach 30% or higher.

Because of the moderately low temperature involved, this study shows that the amount of the electrical power output is low even with a power generation efficiency around 30%. In order to improve the electrical power output and power generation efficiency, this study shows the ways of increasing electrical power output from a radiative-heat-transfer point of view. There are two ways. One way is to find a PV material with a small bandgap as close as possible to the maximum wavelength of a
blackbody distribution (depending on the emissive temperature) and a high external quantum efficiency, and a selective emitter material with very high spectral emittance within the emission band and very low spectral emittance outside the emission band. The other way is to keep the space between the two surfaces as close as possible to increase the thermal power transfer by tunneling interference effects. The latter effect was not examined in this study, but merits consideration in future work.
APPENDIX I

VALUES OF n AND k FOR GALLIUM ARSENIDE (GaAs)
AND INDIUM ARSENIDE (InAs)

Table I-1: Data of n and k for gallium arsenide (GaAs) from Palik (1985)

<table>
<thead>
<tr>
<th>Wavelength (µm)</th>
<th>Index of Refraction (n)</th>
<th>Extinction Coefficient (k)</th>
<th>Wavelength (µm)</th>
<th>Index of Refraction (n)</th>
<th>Extinction Coefficient (k)</th>
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Table I-1: Data of n and k for gallium arsenide (GaAs) from Palik (1985) (continued)

<table>
<thead>
<tr>
<th>Wavelength (µm)</th>
<th>Index of Refraction (n)</th>
<th>Extinction Coefficient (k)</th>
<th>Wavelength (µm)</th>
<th>Index of Refraction (n)</th>
<th>Extinction Coefficient (k)</th>
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Table I-2: Data of $n$ and $k$ for indium arsenide (InAs) from Palik (1985)

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APPENDIX II

CURVES OF THE EXTERNAL QUANTUM EFFICIENCY OF In$_{x}$Ga$_{1-x}$As DEVICES GROWN LATTICE - MISMATCHED ON InP SUBSTRATES

Figure II - 1: Curves of external quantum efficiency of three types of the In$_{x}$Ga$_{1-x}$As without an antireflecting coating (Coutts et al. 1996)
Figure II - 2: Curves of the external quantum efficiency of In$_{x}$Ga$_{1-x}$As with an antireflecting coating (Wojtczuk et al. 1994)

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Figure III – 1: Curve of the spectral emittance of a 40% Er – 1.5% Ho YAG thin film selective emitter (Lowe et al. 1994)
Figure III - 2: Curve of the spectral emittance of a 25% Ho YAG thin film selective emitter (Lowe et al. 1994)
APPENDIX IV

CURVES OF THE NORMALIZED NET RADIATIVE FLUX VERSUS GAP SIZE BETWEEN SURFACES

Figure IV: Curves of the normalized net radiative flux vs. gap size between surfaces at 300 K and 320 K (Whale and Cravalho, 1997)
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Culbreth, W., 1990, Least Squares Curvefit Program, Civil Engineering Department, University of Nevada, Las Vegas.


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University of Nevada, Las Vegas

Yan Xu Graduate Student

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Special Honors and Awards:
1995 Dean's Honor list, the College of Engineering
University of Nevada, Las Vegas

Thesis Title: A Study of Thermal Exchange in a Thermophotovoltaic (TPV) System at
Moderate Temperature

Thesis Examination Committee:
Chairperson, Robert F. Boehm, Ph.D
Committee Member, William P. Graebel, Ph.D
Committee Member, Yi-Tung Chen, Ph.D
Graduate Faculty Representative, Rahim Khoie, Ph.D