Thermophotovoltaic Generation

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***Abstract*—The goal of this work is to model and simulate solar thermophotovoltaic generation process in MATLAB. In this paper, tantalum photonic crystal substrate is used as an absorber and emitter, it is assumed to have unity emissivity and reflectance. Gallium antimonide photovoltaic (PV) cell is used to convert the optical energy generated from the emitter to electrical energy. An array of six PV modules is connected in parallel to give a rated capacity, is radiated by the radiation from the emitter. The input power density varies with corresponding change in emitter temperature. The simulation result gives the relationship between emitter temperature, wavelength of emitter radiation, input power density from the emitter and output electrical power of the PV array. Voltage-current and voltage-electrical power characteristics are also obtained.**

***Keywords*—Thermophotovoltaic; Tantalum(Ta); Gallium antimonide (GaSb); Emissivity (α); Reflectance (ε); MATLAB.**

I. INTRODUCTION

Solar Thermo-photovoltaic (STPV) energy conversion is a conversion process of heat produce by solar radiation to electricity via photons. A basic solar thermo-photovoltaic system consists of a collector which collect the sun radiated energy and the transfer the heat to a thermal absorber and emitter, where heat is converted to radiation, and a photovoltaic diode cell which convert these radiations into electrical power. Depend on the design the input temperature varies from 900 °C to around 1300 °C, although Thermo-photovoltaic (TPV) devices can extract energy from an emitter with temperature above that of the photovoltaic device. The emitter can be a piece of material or a specially designed structure. Thermal emission is the emission of photons due to the motion of charges when a material is heated. For normal TPV temperatures, most of the radiation lies around infrared frequencies. The photovoltaic diodes absorb some of these photons and convert them into D.C electrical power. The main concern in the design of a TPV system is to match the wavelength, polarization, direction of thermal emission with the conversion characteristics of the photovoltaic cell to achieve the highest efficiency possible, The stray thermal emission reduce the efficiency. Most groups focus on gallium antimonide (GaSb) cells. Germanium (Ge) is also suitable. Controlling the emitter's properties is the main concern in research and development of TPVs. TPV generation can be used as auxiliary power generation for regeneration of lost heat from other power generation systems, such as steam turbine systems or thermal power plant.

The basic principle of operation is similar to that of traditional photovoltaic (PV) where a p-n junction is used to absorb optical energy, generate and separate electron-hole pairs, and in doing so convert that energy into electrical power. In TPV generation the optical energy is not directly generated by the Sun, but by a material called the emitter having a high temperature, which emits radiation. [1].

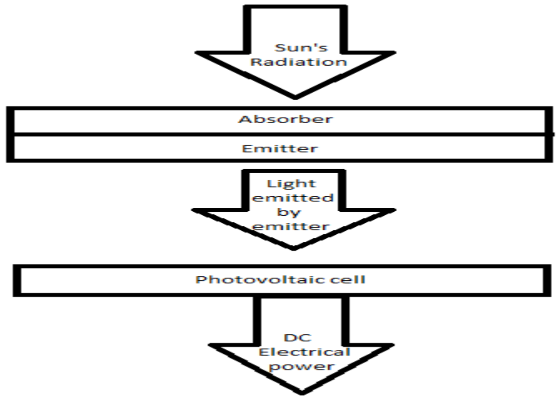

Fig 1: Working of a STVP.

The absorber and emitter can be an array of tungsten pyramids, rare-earth oxides such as ytterbium oxide (Yb_2O_3) and erbium oxide (Er_2O_3), polycrystalline, silicon carbide (SiC) and photonic crystals designed to provide near-unity absorptivity and emission for all solar wavelengths for a wide angular range. This enable it to absorb light effectively from solar sources regardless of concentration [2].

By converting the incident solar radiation to a narrow-band thermal emission matched o the spectral response of the PV cell, STPVs have the potential to overcome the Shockley– Queisser limit for the efficiency of PVs (33%) [2,3,4,].

The efficiency of a TVP is similar to that of the Carnot efficiency of an ideal heat engine and it is given by (1):

$$\acute{\eta} = 1-\frac{T_{cell}}{T_{emitter}} \qquad (1)$$

Where, T_{cell} is the temperature of the PV module. In practical system, T_{cell}~300K and $T_{emitter}$~1800 K, give a maximum efficiency of ~83%. This the Carnot or maximum theoretical efficiency for the system.

II. MODELING

The absorber and emitter used for modeling is a substrate of tantalum (Ta) photonic crystal. Silicon based cells on the other hand, have high band gap (E_g=1.11 eV, λ_g=1.13 μm) and thus are not suitable for thermophotovoltaic application [5,6,7]. Other semiconducting materials such as Ga, GaSb, GaInAs, GaInAsSb have lower band gap [8,9,10,11,12,13]. So the PV cell used for simulation is a gallium antimonide (GaSb) with energy band gap (E_g) of 0.67 eV maintained at 27^0 C [14]. For one module, we connect 40 PV cells in series with short-circuited current (I_{sc}) = 7.34 A and open-circuited voltage (V_{oc}) =0.6 V each cells. Then 6 modules are connected in parallel. The maximum voltage (V_{max}) =24 V and maximum Current (I_{max}) = 44.04 A and the maximum capacity of the model is 1.06 kW.

The sun's radiation energy can be considered as a blackbody radiation. A blackbody is defined as a perfect emitter and a perfect absorber it emits more energy per unit area than any real object, and absorbs all radiation incidents on its surface, without favoring any particular frequencies. The temperature of a blackbody can be determined from its radiant power.

The total intensity emitted by a blackbody, I (W/m^2), at absolute temperature T (K) is given by (2) and empirically determined by Stefan-Boltzmann's law:

$$I=\sigma T^4 \qquad (2)$$

Where, σ is the Stefan-Boltzmann constant (5.67 x 10^{-8} W/m^2 K^4). The surface temperature of the Sun is estimated to be 5800 K [15].

The spectral distribution of a blackbody at a certain temperature is given by (3) Planck's law, which was derived after the Stefan-Boltzmann's law from the basis of empirical results. The Planck's law is

$$I(\lambda) = \frac{2\pi h c^2}{\lambda^5\,[e^{hC/\lambda kT} - 1]} \qquad (3)$$

Where, I(λ) is the spectral emittance, i.e., intensity per wavelength interval of a blackbody in (W/m^3), h is the Planck's constant (6.626 x 10^{-34} Js), C is the speed of light (2.998 x 10^8 m/s), k is the Boltzmann constant (1.381 x 10^{-23} J/K) and λ is the wavelength (m) [15].

The wavelength of the emitter radiation given in (4)

$$\lambda = \frac{b}{T_{emitter}} \qquad (4)$$

where, λ is the wavelength of the radiation in meter (m),

b is the Wein's constant (2.8979 x 10^{-3} m^{3}K),

$T_{emitter}$ is the emitter temperature in Kelvin (K).

The overall efficiency of a TPV is given by (5) as:

$$\eta_{overall} = \eta_{collector} \cdot \eta_{absorber} \cdot \eta_{adiabatic} \cdot \eta_{spectral} \cdot \eta_{cavity} \cdot \eta_{cell} \qquad (5)$$

Certain amount of heat is loss at the absorber and this gives the absorber efficiency ($\eta_{absorber}$). The absorbed heat is transferred to the emitter via thermal conduction while losing a certain amount of heat through the sidewalls. Adiabatic efficiency ($\eta_{adiabatic}$) is defined as the ratio of net emission to absorption. Among the total net thermal emission from the emitter, only high energy photons can generate electron–hole pairs in the PV cell, and the spectral efficiency ($\eta_{spectral}$) is the ratio of the energy of high energy photon to the total net emission. Some fraction of the useful emission is lost along the transfer from the emitter to PV cell. Cavity efficiency (η_{cavity}) is the ratio of the useful emission reaching the PV cell surface to the total useful emission radiated. Finally, electron–hole re combination, thermalization, and non-ideal optical/electrical performance of the PV cell limit the conversion efficiency and the ratio between the maximum power outputs to useful emission at the PV cell is defined as the cell efficiency (η_{cell}) [14].

We can also find out the overall efficiency of TPV as the product of the solar- thermal efficiency ($\eta_{solar\text{-}thermal}$) and thermal-electrical efficiency ($\eta_{thermal\text{-}electrical}$) from (7) [16,17].

$$\eta_{solar\text{-}thermal} = \eta_{collector} \cdot \eta_{absorber} \qquad (6)$$

$$\eta_{thermal\text{-}electrical} = \eta_{adiabatic} \cdot \eta_{spectral} \cdot \eta_{cavity} \cdot \eta_{cell} \qquad (7)$$

The maximum solar-thermal efficiency ($\eta_{solar\text{-}thermal}$) is obtained from (6) by assuming a black absorber, emissivity(α) and reflectance(ε) are equal to 1, and fully concentrated solar irradiation (the solid angles of solar radiation received by the absorber $\Omega_{sun}= \pi$) as follows:

$$\eta_{solar\text{-}thermal} = \frac{\sigma T^4_{sun} - \sigma T^4_{emitter}}{\sigma T^4_{sun}}$$

$$= 1- \frac{T^4_{emitter}}{T^4_{sun}} \qquad (8)$$

$$\eta_{thermal\text{-}electrical} = 1- \frac{T_{cell}}{T_{emitter}} \qquad (9)$$

Therefore, The overall efficiency of a TPV is given by (10), the product of (8) and (9) as [15]:

$$\eta_{overall} = [1- \frac{T^4_{emitter}}{T^4_{sun}}][\,1- \frac{T_{cell}}{T_{emitter}}] \qquad (10)$$

But the thermal-electrical efficiency has the upper limit for emitter temperature. So for temperature >1800 K, we assumed that there will be an increased in the cell temperature, this lead to reduction of 1.1% of the maximum output per degree increase in temperature [18].

Fig.2, shows the MATLAB model of the conversion of heat absorb from the sun's radiation to the optical energy emitted by the emitter. Fig.3, shows the MATLAB model of a thermophotovoltaic generator.

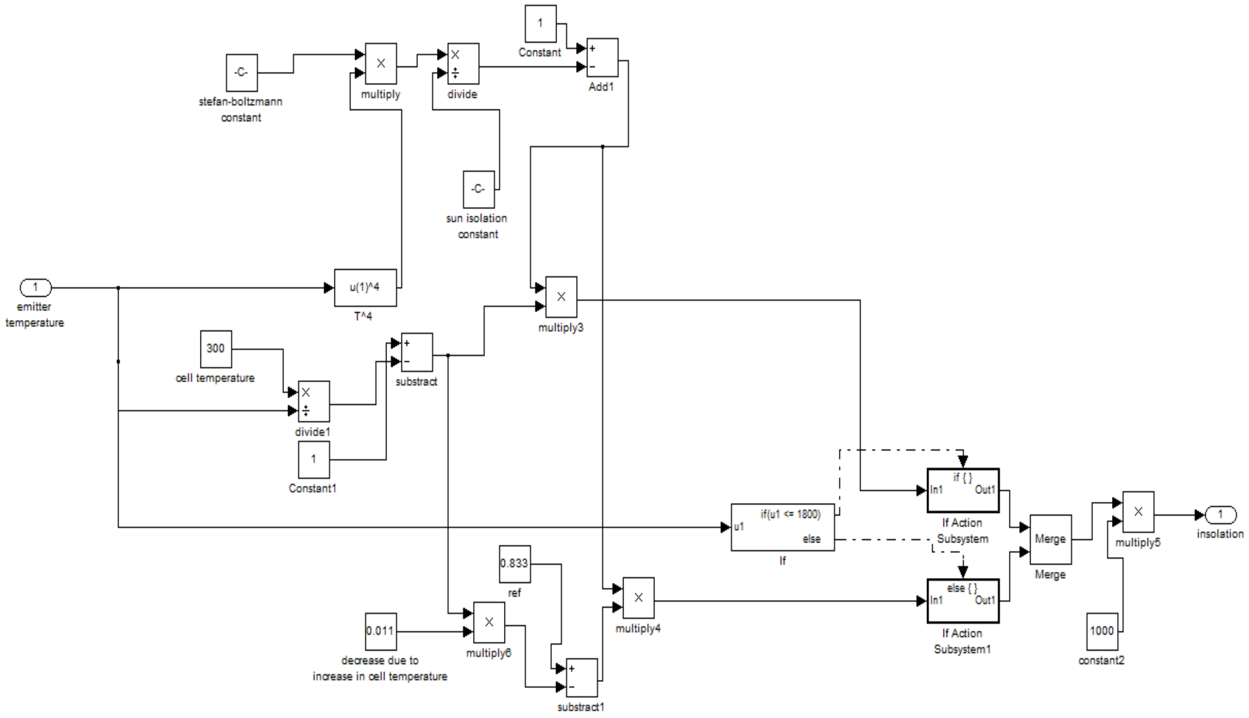

Fig.2 MATLAB model of absorber and emitter.

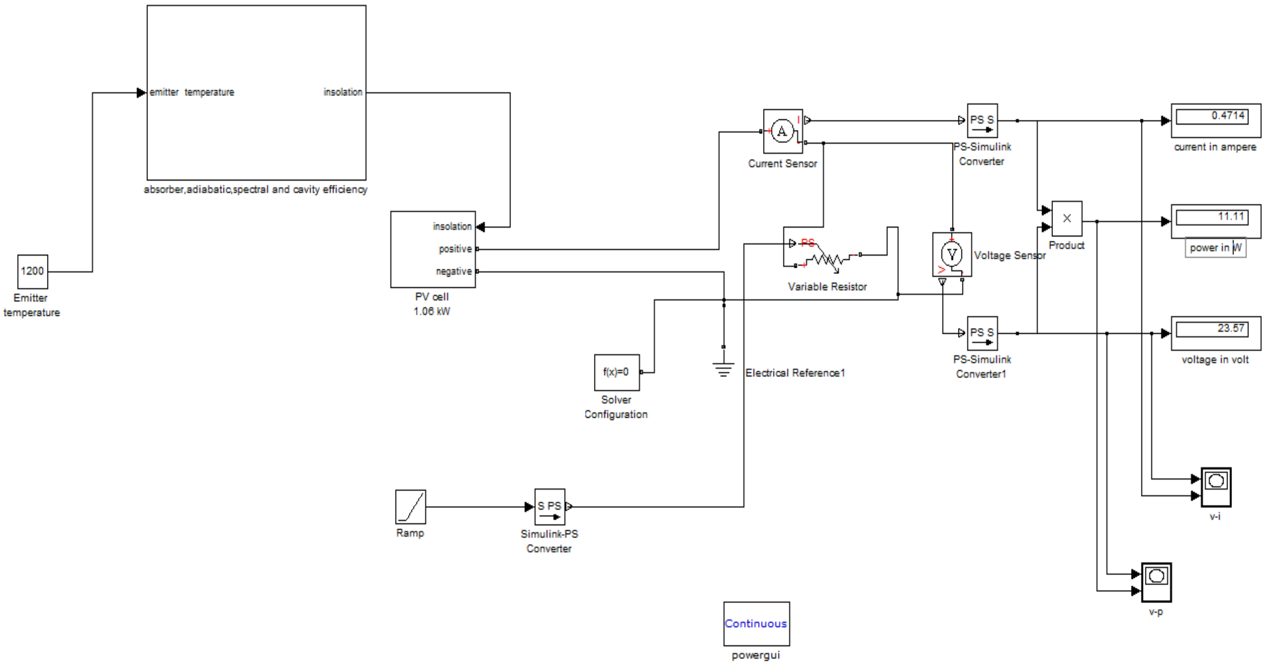

Fig.3 MATLAB model of Thermophotovoltaic generator

III. SIMULATION RESULTS AND OBSERVATIONS

The model is simulated for four different emitter temperatures i.e. 900K,1200K, 1600K and 1800K and maintaining the cell temperature at 300K.

The terminal voltage vs. output current characteristics are obtained as shown in the Fig. 4(a), Fig. 4(b), Fig. 4(c) and Fig. 4(d). We observed that the output current increases with the increase in the emitter temperature. The terminal voltage on the other hand, can reach only to 24 V which is the maximum voltage of the designed array. So, the terminal voltage is dependent of the array designed.

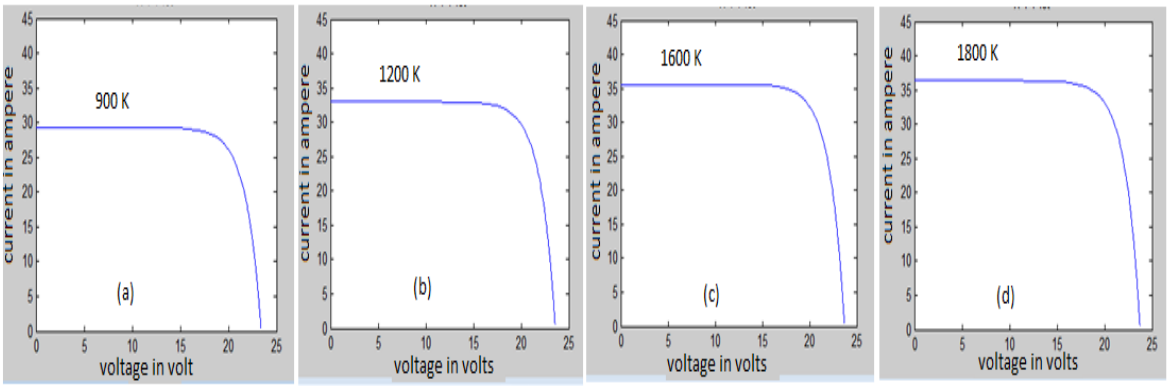

Fig.4 **(a)** V-I characteristics at 900 K emitter temperature. **(b)** V-I characteristics at 1200 K emitter temperature. **(c)** V-I characteristics at 1600 K emitter temperature. **(d)** V-I characteristics at 1800 K emitter temperature

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The Terminal voltage vs. output electrical power characteristics are obtained as shown in the Fig. 5(a), Fig. 5(b), Fig. 5(c) and Fig. 5(d). We observed that the maximum output electrical power increases with the increase in emitter temperature. The output electrical power increases with the increase in the terminal voltage up to a threshold voltage around 20 V then it start to decrease.

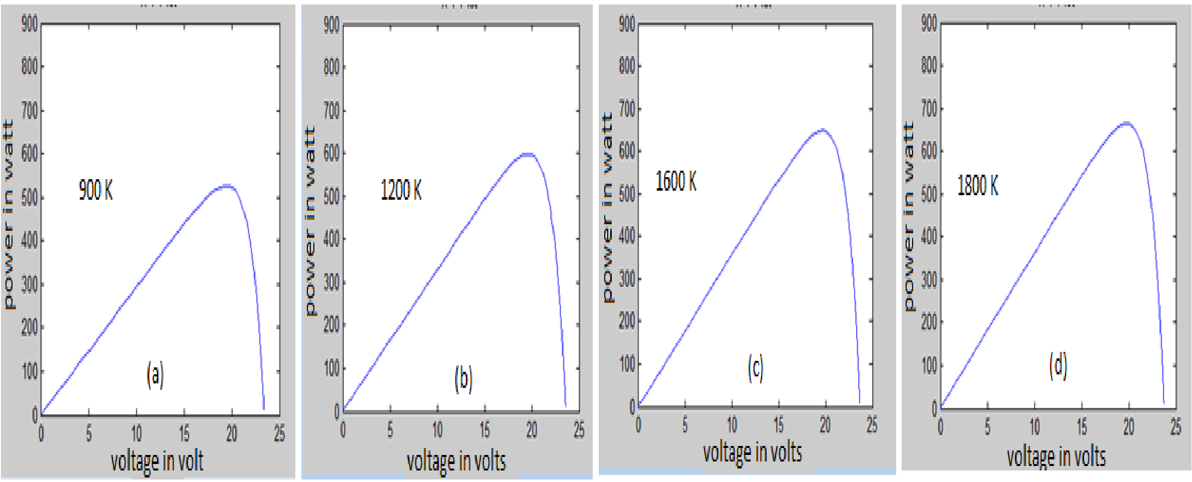

Fig.5 **(a)** V-P characteristics at 900 K emitter temperature. **(b)** V-P characteristics at 1200 K emitter temperature. **(c)** V-P characteristics at 1600 K emitter temperature. **(d)** V-P characteristics at 1800 K emitter temperature.

The emitter temperature vs. input power density characteristic is obtained as shown in the Fig. 6(a). We observed that the input power density increases as the emitter temperature increases. So, higher emitter temperature is desirable from input power density point of view but there is a contrast to this because we observed that the output electrical power decreases when the emitter temperature exceed a threshold temperature of 1800 K as shown in the Fig. 6(b).

The Radiation wavelength vs. Input power density characteristics is obtained as shown in the Fig. 7 (a). We observed that the input power density decreases as the wavelength of the radiation from emitter increases. The maximum input power density is achieved at emitter's radiation wavelength of 15 μm. For application we should chose an absorber-emitter which can convert the thermal power to radiation of very low wavelength because as shown in Fig. 7 (b) the output electrical power increases as the input power density increases although upto a certain point when the PV cell are saturated where it remain constant.

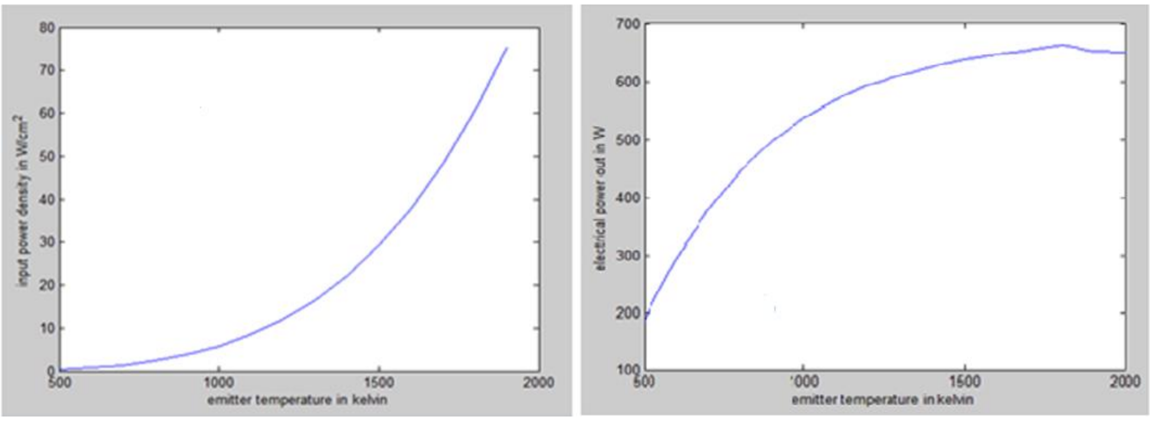

Fig. 6 **(a)** Emitter temperature vs. input power density characteristics **(b)** Emitter temperature vs. output electrical power characteristics.

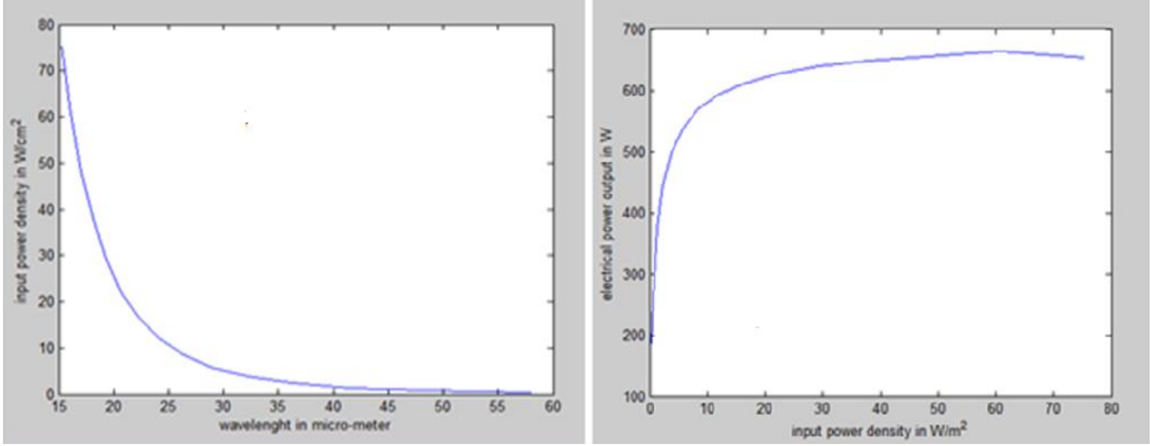

Fig. 7 **(a)** Radiation wavelength vs. input power density characteristics. **(c)** Input power density vs. output electrical power characteristics.

IV. CONCLUSION

In this paper the thermophotovoltaic generation is modelled and simulated in MATLAB based on the theoretical point of view. The absorber and emitter are assumed to be perfect black body radiation. For a desired output terminal voltage the PV cell use in the design should be considered as depend largely in the design. It is a known condition that for a higher electrical output power higher input power density is required. The input power density depends upon the emitter temperature but there is a threshold value up to 1800 K, when the input power density will increase with the increase in the emitter temperature then it will start to decrease. As the emitter temperature increases the PV cell temperature goes on increasing and the resistivity of the circuit also will increase. The wavelength of the radiation from the emitter also should be very low in term of Nano-meter to obtain maximum input power density.

This method could be applied to absorb the waste heat from the furnace of large thermal power plant or any large manufacturing factories which used large amount of fuel. The challenges is to develop efficient absorber, emitter and lower band gap semiconducting cells.

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