An Ultra Compact High Efficiency Thermo-Photovoltaic System for Electricity Generation

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Abstract- In this work, a compact thermo-photovoltic system has been designed and analyzed. The novel system uses a certain gas as an emitter of electromagnetic radiation with discrete wavelengths, this feature eliminates one of the most important factors that lower the efficiency of the ordinary solar systems. Moreover, mathematical expressions predicting the overall efficiency were derived. The mathematical expression indicates that the system's efficiency does not depend on the concentration factor or the solar intensity, However, the only terms that control the efficiency are the absorptivity, the sink reservoir temperature (solar panel temperature) and the source temperature (the absorber temperature). Further, for the purpose of increasing the system's performance, it was proposed to decrease the sink temperature by connecting the system to cooling fins that extend to reach the frost layer in the underground which offers an invariable temperature along the year. The proposed design can be utilized in open areas where it can be irradiated by the solar flux. In addition to that, it can be used in some industrial furnaces which offer high temperatures that would dramatically increases the systems efficiency reaching the theoretical predictions. As a case study the use of the mercury vapor as an emitter where discussed and an estimate of the system efficiency indicated that it may, theoretically, reach 85%. The costs of such a system is found to be relatively high, but taking into consideration the high efficiency of the system and the utilization of the waste heat in industrial furnaces, the cost of such a system may be justified.

Keywords Renewable Energy; Solar Energy; Thermo-photovoltic.

1. Introduction

Solar cells are important source of electrical energy. Although solar energy is a relatively cheap and green source of energy its efficiency is rather small and in an ordinary PV cell the maximum efficiency cannot exceed the Shockley–Queisser limit or the detailed balance limit. The major sources of loses that forms the balance limit in PV systems are due to blackbody radiation, recombination and spectrum loses. The blackbody radiation depends on the temperature of the system as the losses term due to the blackbody radiation is ($A \, \varepsilon \, \sigma T^4$). This term forms about 7% of the losses. While the recombination losses forms about 10% of the losses. On the other hand, the spectrum losses forms the major part of the losses as most of the sun light is not absorbed in a single-junction PV cell [1]. Hence, most of the recent research is toward improving the efficiency of PV systems.

Many techniques have been proposed and applied for surpassing the Shockley–Queisser limit. The most important example is multi-junction photovoltaic cell where various p-n junctions are used to absorb most of the incident solar flux. Other techniques are the light concentration, impurity photovoltaic, photon up conversion, hot electron capture, multiple excitation generation, fluorescent down conversion and thermo-photovoltaic down conversion [2-7].

Thermo-photovoltaic-TPV solar systems are techniques developed for surpassing of the Shockley–Queisser limit or detailed balance limit. The thermo-photovoltic systems relay on the conversion of heat into electricity via photons, the system consists of an absorber/ emitter and a solar PV, the absorber/emitter absorbs the solar energy and converts it to heat while in the same time emitting the energy in the form of electromagnetic radiation. Usually the emitter is made of polycrystalline silicon carbide, tungsten, rare-earth oxides or photonic crystals [8,9].

The efficiency of thermo-photovoltic systems has been discussed and many techniques have been proposed for the improvement of their efficiency. The theoretical efficiency of the system has been estimated to have an upper bound of

85% [7,9,10]. The sources of inefficiency are the filter, the emitter, the geometry and the converter. The emitter's losses are due to the deviation from the perfect absorber/emitter (black-body), in addition to that, those photons that are emitted with energy that is not in the band gap energy may be lost. The filters contributes to losses by reflecting only a small percentage of the non-proper wavelengths back to the emitter while converters losses are represented by the non-radiative recombination and ohmic losses. Geometry is a major factor, that is the ideal geometry should provide converters everywhere around the emitter [7,10-13].

In this work, a high efficiency thermo-photovoltic system with most of the major loses avoided is proposed. The proposed system consists of a configuration where the absorber/emitter surrounds itself and then the reflected radiation from the absorber/emitter is reabsorbed by the system itself. The solar flux is concentrated and directed through a small hole where it enters the system (figure 1). Because of the special geometry of the system; most of the incident energy is absorbed by the system while the portion that is reflected is reabsorbed by the system itself because the spherical geometry of the system offers the absorber everywhere (neglecting the very small light entrance) and then the absorbed energy is then transferred in the form of heat to an emission gas where the atoms are exited and then the light with certain known discrete wavelengths is emitted. This would eliminate the problem of the spectrum losses.

2. General Design

The proposed design suggest the converting of the continues solar spectrum into a discrete and known electromagnetic radiation with certain wavelengths that could be absorbed by a single solar panel that is single or two or three – junction cell which depends on the wavelengths of the produced electromagnetic radiation.

The main concept is based on the conversion of the solar energy into heat, and then using this heat to excite a certain gas inducing it to emit its emission spectrum (characteristic line spectrum). Converting the solar energy to direct heat is a very efficient process that may have 98% efficiency in compact and well-designed systems [14].

Figure 1. Shows the general proposed configuration of the system where the compact system is formed of multiple stages were the solar energy will pass along each one of them in series. the system is a spherical like configuration which consists of three concentric spherical shells (Figure 1).

It is obvious from figure 1. That the solar radiation is concentrated and directed (using a concentration mirror) to the entrance of the system by passing through the opening indicated by point number 1. The cavity in the system is evacuated in order to avoid any attenuation or reflection of the incoming solar radiation near the entrance. The solar flux would heat the rough black heat absorber (black metal plate-the inner most spherical shell). The imparted heat would transferred to the emission gas that is encapsulated between the metal absorber and the transparent spherical glass cover and hence excites the gas. The excited gas would emit electromagnetic radiation with certain discrete wavelengths, the emitted spectrum characteristics depends on the gas used and on its conditions (to be discussed in the next section). The emitted light would travel toward the photovoltaic cell (the inner surface of the outer most spherical shell) through a vacuum cavity where it will be absorbed and transformed to power on the remaining parts of the system.

In figure 2, the compact system is assumed to contain the heat source inside it (e.g. a furnace), this assumption is important since the system shown in figure.1 may suffer sufficient losses even with the utilization of concentrating mirrors. In addition to that, the system in figure .2 is assumed to be coated with a thin metal sheet that is connected to fins that extends to the underground in order to utilize the constant underground temperature that could be obtained below the so called frost layer (3-6 m deep), this temperature usually takes a value that equals to the average temperatures of the atmosphere over the seasons (12-15 °C on Mediterranean climate regions), the utilization of the underground low temperature would increase the Carnot cycle performance. The described fins should be insulated from the soil except at the fin bottom tip.
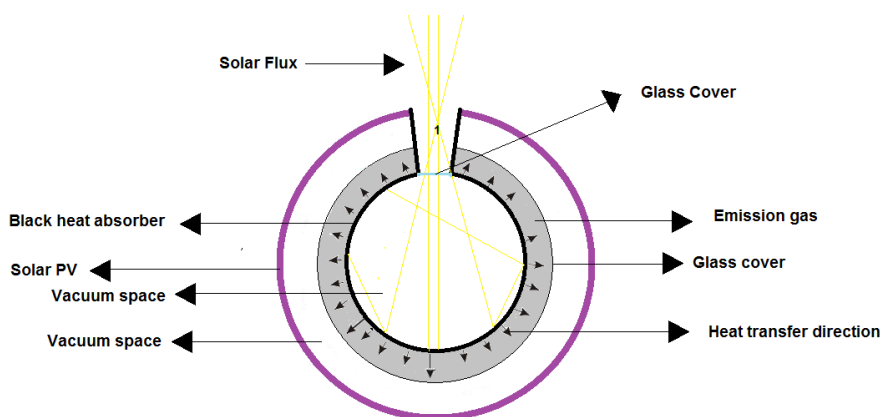

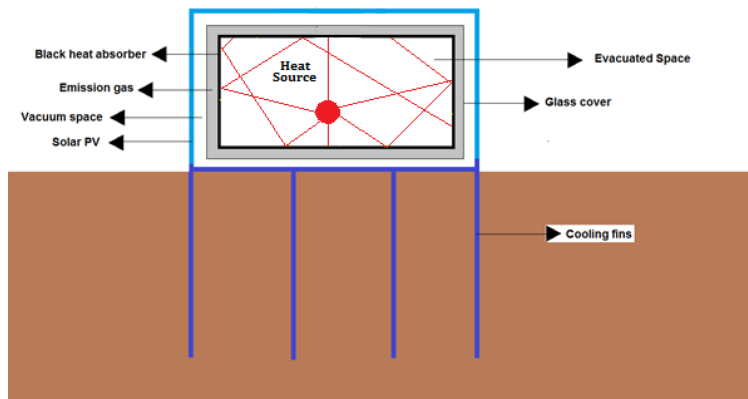**Fig. 1.** The general configuration of the proposed system- sagittal section.

Fig. 2. The general configuration of a furnace heat source with geothermal cooling.

3. Analysis and Discussion

The amount of energy needed to ionize a mole of certain element is called the ionization energy, so by heating a mole of the material the energy of ionization or less is imparted to the element and hence the atoms are excited then the emission spectrum is produced. Various technologies have utilized this physical phenomena, among these are the light sources [15-17]. According to the studies in this field the efficiency of such light sources are highly efficient. For example the compact fluorescent lamp efficiency could be above 80%.

In the system shown in figure 1 the efficiency of the absorber (rough-black heat absorber) is:

$$\eta_{Absorber} = \frac{Q_{absorbed} - Q_{lost}}{Q_{solar\ flux}} \quad (1)$$

While the efficiency of the PV system is:

$$\eta_{Carnot} = 1 - \frac{T_{sink}}{T_{source}} \quad (2)$$

For the terms in eq. (1), the Q_absorbed is that absorbed by the heat absorber from the incident solar flux. On the other hand, The Q_lost in the system is only due to the part of solar flux that is reflected and lost through the entrance to the outside. Those loses could be neglected as the entrance area is considered to be very small, in addition to that the circular configuration of the system will allow the re-absorption of the irradiated energy and hence if the overall loses are considered to be neglected. then the terms in equation (1) are as follow:

$$Q_{absorbed} = \alpha Q_{Solar} \quad (3)$$

Where α is the absorptivity of the black heat absorber.Taking into consideration that the loses in the system are very small as the configuration of the system allows the re-utilization of the emitted radiative heat loses. So Q_lost could be considered negligible. Then :

$$\eta_{Absorber} = \frac{\alpha Q_{Solar}}{Q solar} = \alpha \quad (4)$$

The assumption that the losses are negligible is justified since the emission term A ε σT^4 would be re-absorbed by the system itself, in addition to that, the losses due to the above opening could be neglected and may be reduced by keeping the opening area very small with respect to the total surface area of the system (occupying a very small solid angle).

And the overall TPV system efficiency could be found to be:

$$\eta_{sys} = \eta_{Absorber} * \eta_{Carnot} = \alpha \left(1 - \frac{T_{sink}}{T_{source}}\right) \quad (5)$$

As an example, if a system is fabricated with an absorber of absorptivity α=1 and an absorber/emitter temperature of 1000 K and solar cell temperature of 300 K.

$$\eta_{sys} = \eta_{Absorber} * \eta_{Carnot} = 1 * \left(1 - \frac{300}{1000}\right) = 0.7 = 70\% \quad (6)$$

From equation (5) it is obvious that the system's efficiency would keep increasing as the source temperature increase and the sink temperature decreases. Referring to figure 2 above the proposed system utilizes the underground low temperature as a sink reservoir, this temperature is nearly stable along the year and takes a value that equals to the average temperature variations in the atmosphere. As an example, experiments indicate that at a depth of 6 m the under stable underground temperature is about 12-15 °C.

If we consider that the sink reservoir temperature is considered to be 12 °C (285-K) and a source temperature of 2000 K then from figure 5 it could be found that the corresponding system efficiency is 85.7%. In addition to that,

other sink reservoirs may be utilized, among them are the liquid nitrogen that may offer very low absolute temperatures and hence the efficiency is greatly improved. Figures 3 through 5 discusses the effects of the variations of different governing parameters on the systems efficiency.

In figure 3, the variation of the efficiency with respect to the source temperature (absorber / emitter) is studied for different absorptivity values. Below 2000 K the system is highly sensitive for the absorber/emitter temperature. It is also noted that as the absorptivity increases the response of the system for the increase in the source temperature slightly decreases. The source temperature ranges between 300 K to 4000 K. The upper limit of the range seems to be high for the open area solar fluxes but on other applications, such as industrial furnaces where the application requires such high temperatures, this range may be justified. Figures 4 and 5 discuss the change in the efficiency with respect to the sink temperature. At law sink temperatures the systems efficiency is greatly increased. So in order to increase the system's efficiency the source temperature should be increased or the sink temperature should be decreased. It is obvious the decreasing the sink temperature to extremely low values is a complicated process while increasing the source temperature is much easier. For the purpose of the sink temperature reduction the relatively low frost layer temperature could be used, from figure 4. It is obvious that the application of the frost layer temperature as a sink temperature would enhance the efficiency better at lower source temperatures. On the other side, for increasing the source temperature, the system could be applied in applications where heat is rejected and been lost (such as industrial furnaces).

Finally, it worth mentioning that while the small opening of the system limits amount of the solar energy that could come into the large cavity (figure.1), figure.2 does not suffer from this deficiency as the heat source is included inside the system and then the majority of the heat generated is absorbed in the system. Moreover, the using of Carnot cycle to analyze the system is questionable because the Carnot cycle behavior is an ideal behavior, but still, this analysis provide us with a good estimation f the performance of such a compact system (figures. 1 and 2).
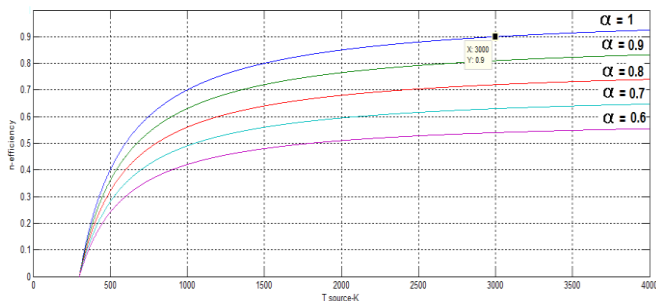

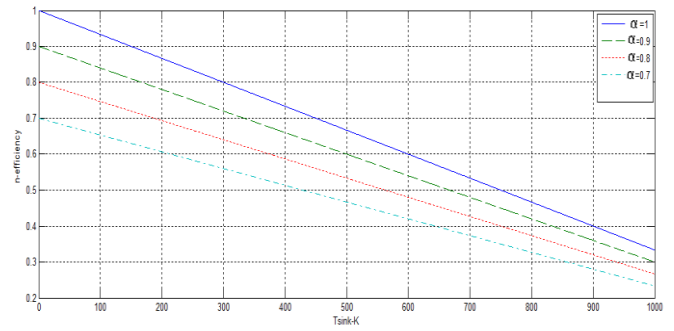**Fig. 3.** The system's efficiency with the source temperature (absorber temperature) T sink=300 K.

Fig. 4. The system's efficiency variation with the sink temperature (atmospheric, geothermal..etc) at various values of the absorptivity.
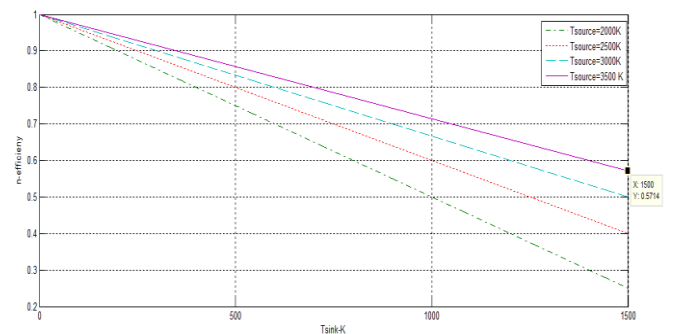

Fig. 5. the system's efficiency variation with the sink temperature (atmospheric, geothermal..etc). at various values of the source temperature.

4. Design parameters and experimental tips

The systems shown in figures 1 & 2. Consists of various layers. If each layer of material is chosen in such a way that they function perfectly then the predicted theoretical efficiency would be reached.

In order to enhance the negligible losses assumption, special care would be should be taken for the design of the solar flux entrance components design. The solar flux would pass through the opining that is separated from the outside by a glass cover that is transparent. In addition to that, the opening area relative to the total surface area should be small, that is the solar flux should be concentrated and directed to a specific point. Moreover, the central cavity evacuation would reduce the probability for near surface reflection to occur. These design aspects would assure that the irradiated energy for the hot parts (A ε σT^4) is re absorbed in the system itself.

The most inner spherical space is evacuated in order to eliminate the convection heat transfer and to remove any possible absorption for the incoming solar flux. The other evacuated region In the system is the gap separating the emission gas from the solar PV coating.

Another important aspect regarding the absorption material is To enhance the absorption by selecting a material that possess excellent heat transfer properties and other

properties that may enhance the absorption of most of the incident light, for example some important tips regarding this issue is to design a black absorber with a rough surface. The absorber will transfer the absorbed heat to an emission gas that would be excited and then emits it emission spectrum with discrete wave lengths, emitted spectrum would be totally absorbed by the solar panel attached to the outer prefer of the system.

The choice of the emission gas is open and depends on the specific parameters and conditions of the area where the solar PV is to be installed. As an example if the emission gas is mercury vapor then the atoms would be excited, then emit the absorbed energy in the form of ultraviolet light, this emitted light could be directly absorbed by the solar PV or could be passed through a phosphor coating that would convert the ultraviolet to visible light. Experimental studies indicates that some well-designed and compact fluorescent light sources has an efficiency of around 85% and more than 78% of the emitted energy is in the ultraviolet region [18], so if a double junction PV cell is used then most of the produced energy would be utilized. On top of that, it should be noted that by using the mercury vapor as an emission gas the produced spectrum would be free of infrared which usually reduces the solar PV efficiency [18-22]. Many other gases could be used with various temperature and pressure combinations that would definitely affect the quality of the produced spectrum. Moreover, the choice is open to choose a molecular combination of gases that would yield e certain desired spectrum. These tips may help in understanding the process and then considering its valuable potentiality to enhance the solar systems efficiency.

5. Conclusion

In This paper a compact thermo-photovoltic system has been proposed. The novel system uses certain gas as an emitter of electromagnetic radiation with discrete wavelengths. This feature eliminates spectral losses which lowers the ordinary solar system's efficiency. Hence, the efficiency of the compact thermo-photovoltaic is very high due to the negligible losses radiative, elimination of spectral losses and the choice of suitable materials. Mathematical expressions predicting the overall efficiency of compact system was derived. the mathematical term indicated that the system's efficiency does not depend on the concentration factor or the solar intensity, However, the only terms that control the efficiency are the absorptivity (of the absorber), the sink reservoir temperature (solar panel temperature) and the source temperature (the absorber temperature). To increase the system performance it was proposed to decrease the sink temperature by connecting the system to cooling fins that extends through the ground to reach the frost layer in the underground which offers an invariable temperature along the year due to the thermal inertia. The system's efficiency was calculated and it was found that it may exceed 90% in the cases where the system has a near perfect absorber (absorptivity reaches one). The application of such a system may be extended from being used in open area and been irradiated by the solar flux to be used in some industrial furnaces which offer high temperatures that would

dramatically increases the systems efficiency. The costs of such a system is found to be relatively high, but taking into consideration the high efficiency of the system and the utilization of the waste heat in industrial furnaces the cost of such a system may be justified. The analysis of the system using Carnot efficiency is ideal but still representative for the system and can provide us with a good estimation of the system's behavior. Finally, it worth mentioning that while the small opening of the system limits amount of the solar energy that could come into the large cavity (figure.1), figure.2 does not suffer from this deficiency as the heat source is included inside the system and then the majority of the heat generated is absorbed in the system.

Nomenclature

$Q_{absorbed}$ = The energy absorbed by the absorber (J)

Q_{lost} = The energy lost from the absorber (J)

$Q_{solar\ flux}$ = The total solar flux energy received (J)

Tsink = The PV temperature (K)

T_{source} = The absorber temperature (K)

Greek Letters

$\eta_{Absorber}$ = Efficiency of the absorber (%).

η_{Carnot} = Efficiency of the Carnot (%).

α = Absorptivity.

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