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THERMOPHOTOVOLTAIC CONVERSION AND COMPARATIVE STUDY ON THE PERFORMANCE OF CONVERSION OF THE FAR-FIELD REGIME AND NEAR-FIELD REGIME

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ABSTRACT
TPV conversion is nowadays a serious candidate for the conversion of radiated heat into electricity. It is not a substitute for PV, on the contrary it allows to extend the conversion into electricity of the electromagnetic spectrum. This work is a review of the TPV sector on the one hand but also a comparative study of the two regimes of the TPV industry. This study allows us to know that near field offers the best conversion efficiency limits.

Keywords: Thermophotovoltaic, conversion, near field, far field, efficiency.

1. INTRODUCTION
The principle of thermophotovoltaic conversion (TPV) is the same as that of photovoltaic (PV) conversion. However, in the PV system, the radiation source is the sun which can be assumed to be a blackbody with a temperature around 6000K far from the earth (about 150 × 106 km). In the TPV the temperature of the transmitter is much lower **[1]**, but the photovoltaic cell is placed much closer to the latter. It is a few centimeters in the case of the far field or even a few nanometers in the case of the near field. TPV conversion has major advantages over PV conversion. The first is the high power density and the second is the 24 hours of operation rather than an average of 8 hours a day for the sun. These benefits translate into 300 times more kWh per unit area for POS power circuits. There are two types of POS conversion, far-field and near-field **[2-5]**.

This article is a review of the two types of TPV conversions namely far-field and near-field conditions.

Far-field thermophotovoltaic systems

A. Principle of operation
The operation of the TPV cell is based on a photovoltaic cell irradiated with a thermal flux in the infrared range suitable for efficient conversion to electricity. This radiative flux is delivered by a suitable transmitter heated by the source.

B. Components of a TPV system
A thermo-photovoltaic system comprises several components: the heat source, the transmitter and / or the filter and the thermophotovoltaic cell.

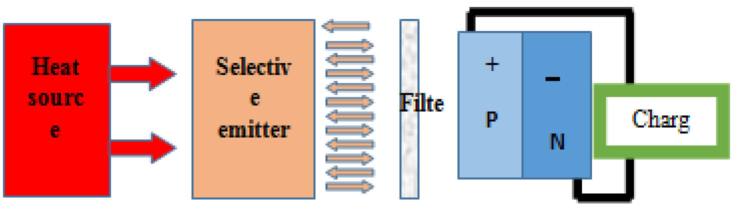

Figure 1: Operation of a far field TPV cell

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The heat source plays a decisive role in the operation of a TPV cell because it makes it possible to emit photons with wavelengths of energy proportional to its temperature. The sun is not necessarily the only source of heat, other sources can be used and give higher efficies.

Figure 2: TPV device with a cooling system [6]

The important component of a TPV generator is the transmitter [5]. The adaptation of the emission spectrum with the spectral sensitivity of the cell is the major difficulty encountered in the performance of the generator. Indeed, the cell absorbs only the photons having an energy higher than that of the forbidden band which corresponds to a small part which will be transformed into electricity. Therefore, to increase the efficiency of the system, the use of a selective transmitter is very important. Its role is to transform the heat it receives into an emission spectrum sensitive to the characteristics of the cell. Several materials, such as rare earths, silicon carbide and photonic crystals, have beenused to develop selective emitters.The filter is placed just after the transmitter and its role is to filter the emission spectrum from the transmitter. The TPV cell only converts photons with an energy higher than the forbidden band of the cell. The remaining energy is absorbed by the cell. It is a lost energy and an obstacle to the efficiency and durability of the device.

C. Far-field thermal radiation

Spectral emissive power

The power below, equation (1), reflects the emission of a gray body depending on the emissivity. In our study, the gray body is nothing but silicon carbide which is heated by a butane cylinder. The SiC will in turn radiate heat to the TPV cell **[2-4].**

$$P(E,T) = \varepsilon \frac{2\pi E^3}{h^3 c_0 \left[\exp\left(\frac{E}{K_B T} \right) - 1 \right]} \quad (1)$$

Heat flux exchanged between two parallel surfaces in far-field

Radiant heat transfer between two parallel surfaces can be calculated using the view factors. We consider in our case that the emitter and the photocell constitute the two parallel bodies. The heat flux between the transmitter and the cell is given by the relation:

$$\Phi = n\sigma\left(T_1^4 - T_2^4\right) \quad (2)$$

The temperature of the cell considered is 300 K. It has been supposed that the heat transfer takes place in the vacuum therefore n = 1. It can be seen that the flux does not depend on the distance that separates the emitter and the cell. but only body temperatures in exchange.

1. NEAR FIELD

2.1 Principle of operation

Near-field TPV system components are fewer and simpler than those in the far field. However, they work the same way, but the physical laws that govern them are not the same because of the difference in the distance between the source and the TPV cell [7-10]. Figure 3 is a TPV device that operates in the near field. In this figure we have two essential parts namely the transmitter and the TPV cell. The first is characterized by its radiative temperature, Trad, and its emission frequencyωWhile the second is characterized by its temperature Te and its absorption coefficientα.

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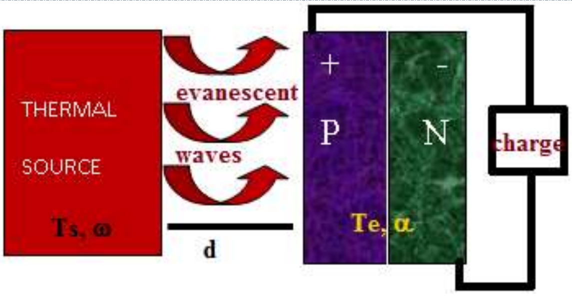

Figure 3: Operation of a Near Field TPV Cell [2]

The distance between them is of the order of a nanometer. As a result, the cell receives two types of waves: progressive waves and evanescent waves. In the far field, only the first mentioned are involved. In this case, we also have surface waves that reach the cell through the tunneling effect of radiation [11-13].

2.2 Near-field thermal radiation study

Heat transfer between two flat surfaces

To account for the contributions of evanescent waves, a small separation area is needed to evaluate the mean⟨S(r, ω)⟩ of the Poynting vector modulus, which can be expressed as a function of the geometric boundary conditions and properties of the materials. . The heat flux module corresponding to the frequency ω is
q(d, ω) = ⟨S_z(d, ω)⟩ and can be written as the sum of the two terms [14]:

• the contribution of propagation wavesq^{prop}(d, ω) which is given by:

$$q^{prop}(d,\omega)=\frac{\omega^2}{2\pi^2c^2}\left[\Theta(\omega,T_1)-\Theta(\omega,T_2)\right]\times\sum_{q=s,p}\int_0^{\omega/c}\frac{k_{II}dk_{II}}{k_0^2}\left[\frac{\left(1-\left|r_1^q\right|^2\right)\left(1-\left|r_2^q\right|^2\right)}{4\left|1-r_1^qr_2^q\exp(2ik_\perp d)\right|^2}\right] \quad (3)$$

• the contribution through evanescent waves, q^{evan}(d, ω) is:

$$q^{evav}(d,\omega)=\frac{\omega^2}{2\pi^2c^2}\left[\Theta(\omega,T_1)-\Theta(\omega,T_2)\right]\sum_{q=s,p}\int_{\omega/g}^{\infty}\frac{k_{II}dk_{II}}{k_0^2}\exp[-\operatorname{Im}(k_\perp)d]\left[\frac{\operatorname{Im}(r_1^q)\operatorname{Im}(r_2^q)}{\left|1-r_1^qr_2^q\exp[-2\operatorname{Im}(k_\perp)d]^2\right|}\right] \quad (4)$$

r_1^q and r_2^q are the Fresnel reflection coefficients for the polarization s (q = s) or the polarization p (q = p) of the two interfaces. By integrating over the entire frequency range, the total flux between the two media is summarized as follows:

$$\Phi(d,T_1,T_2)=\int_0^{\infty}q(d,\omega)d\omega \quad (5)$$

In the end, we ask:

$$X(\omega)=\int_0^{\beta_C}s(\omega,\beta)d\omega \quad (6)$$

After simplification, there is an upper limit of radiative heat flux in the near field, for non-magnetic materials, this is given by:

$$q''_{\max}=X_{\max}\frac{K_B^2}{6\hbar}\left(T_1^2-T_2^2\right)=\frac{K_B^2\beta_c^2}{48\hbar}\left(T_1^2-T_2^2\right) \quad (7)$$

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q "max is the maximum flow of heat, it is obtained when d → 0. It is found that metals with a large imaginary part in the infrared can help to reach such a limit at extremely small distances. However, for distances greater than a few nanometers, the situation is different.

Maximum electrical power

$$P_{EL\,\max} = \frac{(\pi k T_S)^4}{60\pi^2\hbar^3 c^2}\left[\begin{array}{l} 1-\dfrac{\chi(\omega)-1}{\chi(\omega)-1}+\dfrac{k_B T_e}{\hbar\omega_0}(\chi(\omega)-1) \\ .\left\{\begin{array}{l} \left[1+\dfrac{1}{\chi(\omega)-1}\right] \\ \ln\left[1+\dfrac{1}{\chi(\omega)-1}\right]+\left(\dfrac{1}{\chi(\omega)-1}\right)\ln(\chi(\omega)-1)-\left[1+\dfrac{1}{\chi(\omega)-1}\right] \\ \ln\left[1+\dfrac{1}{\chi(\omega)-1}\right]+\left(\dfrac{1}{\chi(\omega)-1}\right)\ln(\chi(\omega)-1) \end{array}\right\} \end{array}\right] \quad (8)$$

2. RESULTS AND DISCUSSIONS

We will now exploit these theoretical results by simulating them using MATHCAD software. We deliberately chose to vary the expressions as a function of u which is a dimensionless variable instead of taking the frequency, the wavelength or even the energy of the gap to be able to manipulate values on our scale. We recall that u is a function of the parameters quoted above(u=E/kT=hυ/kT=hc/kT).

3. 1 Results and discussion on far-field studies

Effects of the temperature of the TPV transmitter on the exchanged flow

Figure 4 which shows the dependence of the heat flux exchanged between the transmitter and the TPV cell. A temperature of the cell operating at 300K was assumed.

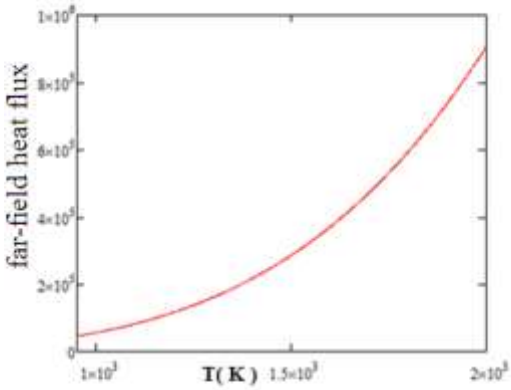

Figure 4: Heat flux between two plates according to the temperature (in K) of the transmitter

We notice that the temperature of the transmitter influences very strongly the increase of the exchanged flow. It has been assumed that the two bodies in heat exchange are parallel. However, the distance separating them is supposed to be important, ie it is greater than the wavelength of the radiation. As a result, only progressive waves participate in the exchange. The evanescent waves remain confined to the surface of the transmitter. Nevertheless it is noted that the flow in exchange is very important. The proof, it is almost of the order of 6 digits for a temperature of 2000K.

It should be noted that part of the thermal energy flow will be transformed into electricity, that is to say the one whose energy corresponds to the energy of the gap. The other part of this energy will have a detrimental effect on the cell if it is not recycled.

Effect of temperature and u on maximum electrical power

Electrical power is a very important parameter for characterizing the performance of a TPV and PV cell. The more important it is the more the performance is. It depends on the optical characteristics of the materials in exchange. These characteristic parameters of the material are grouped in the expression of **Error!**. In the simulation on MATHCAD, we gave the value of 1 to y, the surface of the module being at 1cm2 and varied the temperature of the transmitter.

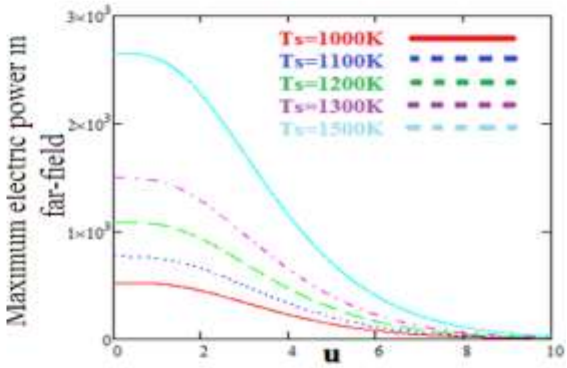

Figure 5: Maximum electric power in far field as a function of u and the temperature of the transmitter

Figure 4 shows the dependence of the maximum yield as a function of the width of the forbidden band Eg. We note that the power increases as a function of the temperature as a function of the low values of the gap energy of the TPV material. Indeed, if the temperature is low, many wavelengths will not be absorbed due to the inadequate gap to incident radiation. If the gaps are high, whatever the temperature, this same phenomenon is also observed.

This confirms once again that low gap materials are the best candidates for TPV energy conversion.

Effect of temperature on the radiative power exchanged

The radiative power is very important for efficient conversion to electricity in the thermophotovoltaic field if the gap of the cell material is adequate. the curve above which reflects the radiative power of the transmitter according to its temperature.

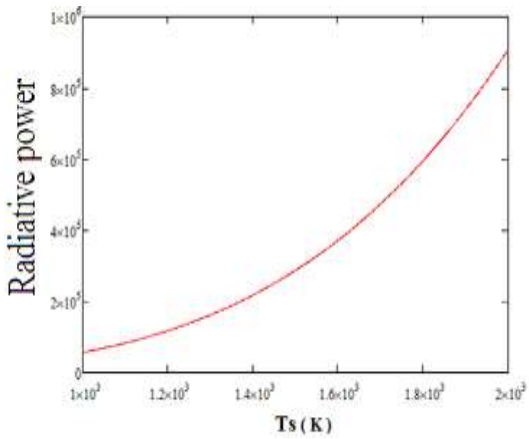

Figure 6: Radiative power of the transmitter according to the temperature

This power strongly depends on the temperature as shown in Figure 5. For high temperatures, the problem is to find the appropriate material for the thermophotovoltaic device and its resistivity at such temperatures.

Maximum conversion efficiency

FIG. 7 shows the far-field TPV conversion efficiencies as a function of u but also of R, which is a quantity that depends on the optical parameters of the TPV device defined in reference [2]. The curves have almost the same profile, except that for which R = 0. The maximum yields evolve with u and with R whose small values give

high yields. Given the definition of R, to obtain a good yield, it is desirable that the emittance$\varepsilon_{Eb}$for the energy of the useful photons ($E_g \leq E$) of the region of the spectrum be very large compared with the emittanceε_{El}, for the low-energy photon region ($0 \leq E$) of the spectrum that can not be converted into electricity.

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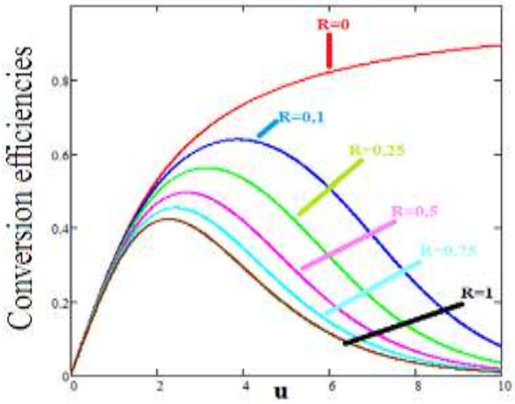

Figure 7: Maximum yield according to u

For this, the use of a spectral control seems obvious by setting up a selective emitter and a control filter. This spectrum of control plays two essential roles:

- optimizes the TPV surface power density by optimizing the transfer of convertible photons from the source.
- optimizes the TPV efficiency by minimizing the transfer of non-convertible photons from the source.

Conversion efficiency of an ideal system

It can be seen that in FIG. 8 the yield increases practically linearly for ug of between 0 and 2 and then slowly increases for the remainder of the values of u. We can see that this yield can reach 90% under ideal conditions. These conditions stipulate that the energies having a wavelength greater than that corresponding to the gap of the material of the cell are not emitted and are totally reflected. Those with a wavelength less than that corresponding to the gap are entirely emitted and not at all reflected. The major work in the far field TPV conversion is dedicated to producing materials that meet these ideal conditions. This is why electric transmitters and increasingly efficient control filters are emerging.

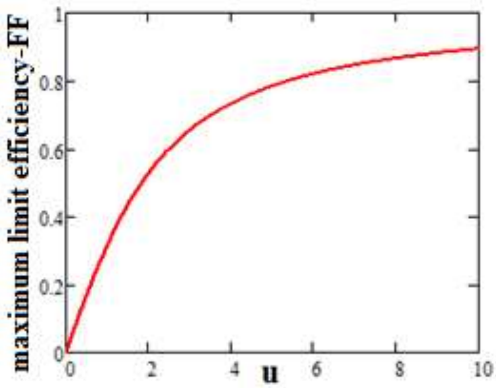

Figure 8: ideal yield based on gap ug

3. RESULTS AND DISCUSSION ON NEAR FIELD STUDIES

4.1 Influence of temperature on the flow

We realized this curve on MATHCAD taking as emitter silicon carbide, SiC, whose maximum frequency is $\omega_{max} = 1{,}79.10^{14}$ rad.$s^{-1}$and the value ofβ_{max} is $\beta_{max} = 50\omega/c$. The temperature of the cell which is nothing other than the InGaAsSb is 300K.

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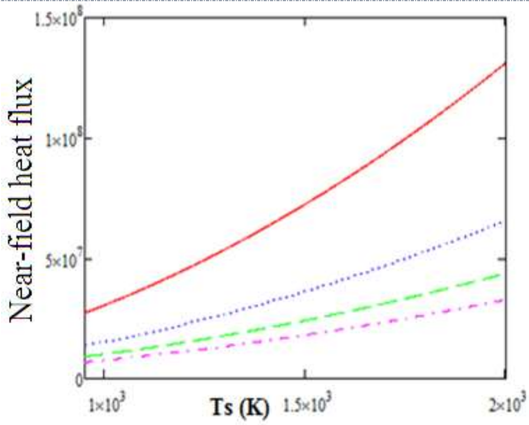

Figure 9: Heat flux exchanged between a silicon carbide emitter and a TPV cell, temperature 300K, as a function of the temperature of the SiC emitter, ω_{max} = 1,79.10^{14} rad.s^{-1} **and the** *value of β_{max} is $\beta_{max} = 50\omega/c$*

In Figure 9, we note that the higher the temperature is higher the flow increases. This is normal because by increasing the temperature, it increases at the same time the amount of heat of the emitter exchanged. We will have the increase related to the surface waves (evanescent waves which are confined to the surface of the silicon carbide which constitutes the emitter) and that related to the progressive waves. For a temperature of nearly 1800K, the power is of the order of 9 figures far exceeding that of the near field.

4.2 Influence of temperature and u on limit electric power

The electrical power characterizes very well the performance of the transmitter. It is the very numerator of the expression of conversion efficiency.

Figure 9 gives the expression of the maximum electrical power as a function of u and the temperature of the transmitter. The most suitable transmitter at InGaAsSb is silicon carbide. That's why we took this tandem.

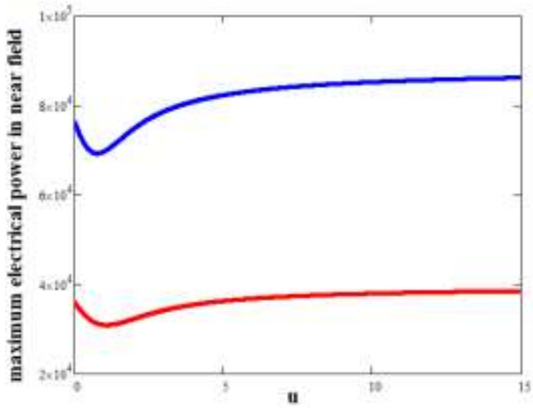

Figure 10: Near-field limit electric power as a function of u

It can be seen that the power varies very slightly beyond the value of u = 2. We notice that it varies very strongly depending on the temperature so we did not take values beyond 1500K so that the figure can contain all the curves. In fact, the values u corresponding to the infrared radiation begin after the value of 3, which is why a slight concavity is observed quite at the beginning of the curve.

A small variation in the temperature causes a considerable variation of the electric power. This is due to the very strong involvement of surface waves once more.

The weakness of the power evolution for a given temperature is due in fact to its low dependence on the gap energy of the material.

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4.3 Influence of temperature and frequency on upper limit of near field TPV efficiency

The conversion yield is a very important part because it predicts the importance of the sector. In the 1990s, she was abandoned because of her low performance. It again aroused interest in the late 1990s with the advent of spectral control and near-field theory.

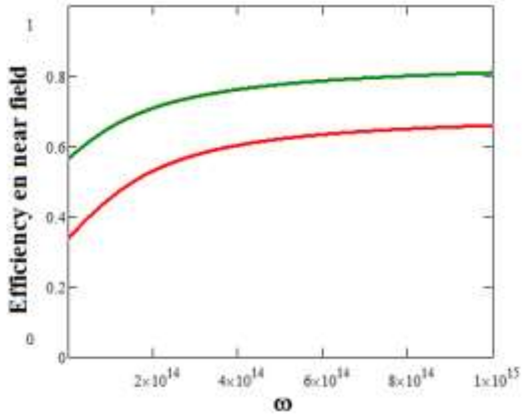

Figure 11: Upper limit of near-field POS performance as a function of frequency

The yield depends very strongly on the resonance frequency of the material but also on the temperature of the silicon carbide. It can be seen that the efficiency can reach 80% for a temperature of 2000K of the emitter at the level of FIG.

Figure 12 gives us the variation of the yield but this time according to the size without dimension u. The observation is the same; yields can reach 80%.

This increase is only due to the presence of evanescent waves that contributes to the conversion process.

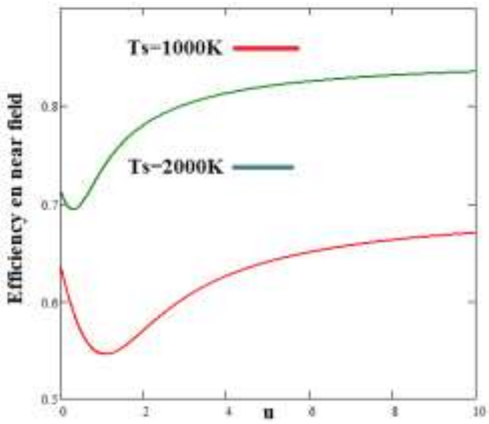

Figure 12: Upper limit of near-field TPV yield as a function of u

This tunneling effect of the radiation contributes to the creation of photocurrent when its waves are in adequacy with the gap of the material of the cell. This process has the almost the same advantage of a monochromatic source radiating a cell.

4. COMPARATIVE DISCUSSION BETWEEN THE TWO FIELDS ON THE RESULTS

After having studied the case of each field, we will now make a comparative study of the latter in order to give a definitive conclusion.

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5.1 Comparison between near and far field heat flux

In each case, we have assumed that the two bodies in heat exchange have a plane geometry and are arranged in parallel. By grouping the two curves on the same axis system in FIG. 13, we see a difference in the variations for the same temperature variations of the emitter.

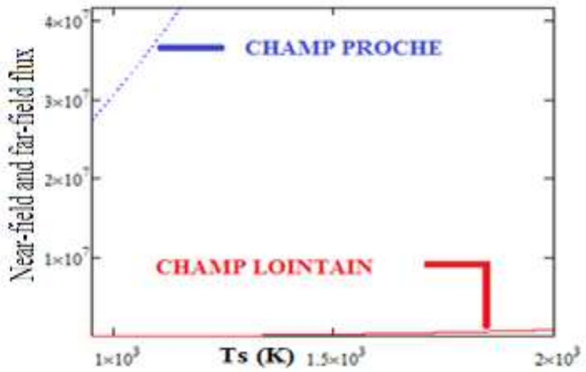

Figure 13: Comparison between the flux exchanged in the regime of the near field and the distant

Figure 4 shows that the flux exchanged in the near field is greater than the far field. This result is predictable because the first regime that takes into account the evanescent waves unlike the second which, in turn, takes into account only progressive waves. Figure 9 gives a comparative study of the two types of field.

These results are predictable because the tunnel effect contributed a lot to the flux in the field. This effect is non-existent in the far field because of the long distance between the transmitter and the cell because the surface waves disappear in the immediate vicinity of the transmitter surface.

5.2 Comparison between the two limit electric powers

Figure 14 consists of two curves with a precise legend. We considered that each of the two cells consists of InGaAsSb with a temperature of 300 K. That of the transmitter being 2000 K. For a temperature of 2000K the value of u for the InGaAsSb is of the order of 3. More the temperature is important plus the value of u of the material is small because the two are inversely proportional.

The curve actually comprises two parts: the corresponding part before the intersection and the part that comes after the intersection. The yellow line separated them in two.

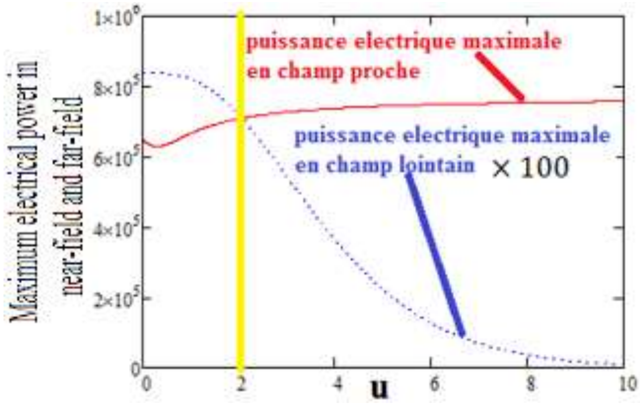

Figure 14: Comparison between near-field and far-field electric powers as a function of u

In the first part, 0≤u≤2, we see that each curve has a different concavity with respect to each other. That of the near field is directed upwards while that of the far field is directed downwards.

In this part we see that the power of the far field is greater than that of the near field while both are in the same temperature conditions. The difference therefore lies in the gap energy because ug.k.Ts = Eg. We can therefore say in this part that the effect of the far field wins it on the near field. In other words, the contribution of the evanescent waves is less important than that of the gaps removed. We can also say that the small gap can not contain both such a great energy. Which is quite common sense.

The second part corresponds to the case where u> 2. It can be seen that the power corresponding to the far field decreases exponentially while that of the near field increases slightly. The difference between the two is very clear. So the effect of the near field begins to impact because the gap is wide enough and surface waves can leave the transmitter to regain the cell.

However, it should be noted that u (InGaAsSb at 2000K) = 3.013. Which means at the moment when the power of the near field is less than that of the far distance it does not concern this material since in this part 0≤u≤2.

5.3 Comparison of the limit of conversion efficiency in near and far fields.

We have seen previously and separately the yield yield of these two types of TPV conversion. We have also studied the two powers that constitute the denominator of the expression of conversion efficiency. That's why the interpretations are the same. This part is a comparison of yields in both fields.

Graph a) of Figure 15 speaks for itself. We see that the difference of these maximums is close to 25%. This shows a clear superiority of the near field limit yield on the maximum far field yield.

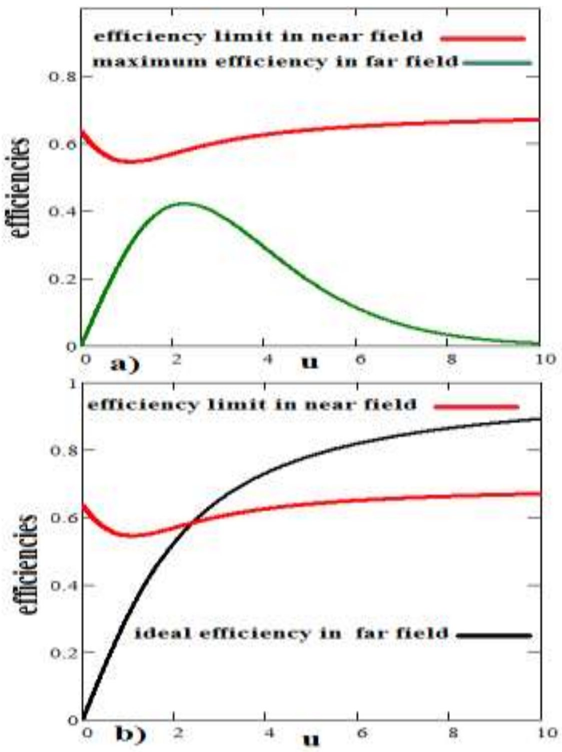

Figure 15: Comparison between near field limit yield and ideal far field yield

Figure 15 (b) shows that an ideal far-field TPV device can outperform the near field function by having a material that can give a high u. However, for these values of high u, we leave completely the field of the infrared. For a silicon-based TPV device (Eg = 1.1 eV) whose emission temperature is 1200 K, the expected ideal efficiency is 90%. The yield of Carnot for a cell whose emission temperature is 300k is 75%. As for the apparatus operating in far field, the expected yield is 72.6%.

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5. CONCLUSION

At the end of this comparison we have seen the superiority, in terms of performance, of the near field on the far field. This confirms the contribution of evanescent waves to the near field. These surface waves, which are confined to the immediate vicinity of the transmitter, contribute to the TPV performance when the distance between the cell and the transmitter is less than the emission wavelength. Graphene and metamaterials offer interesting cleanliness on these modes for a greater contribution of these surface waves.

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