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Study on the efficiency of net thermophotovoltaic conversion, electric and radiative powers according to the separation distance between the cell and the heat source and the temperature

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ABSTRACT
The thermophotovoltaic in the near field in less controlled compared to the far field and photovoltaics. It has generated a lot of research in the literature because of its very interesting results. Among the interesting parameters of its evaluation we have the radiative power, the electrical power extracted and the conversion efficiency. This article studies these electrical quantities according to the parameters such as the temperature of the source, the temperature of the cell and the separation distance between the source and the cell. The article informs us that the maximum efficiency is of the order of 24%. However, this performance can be surpassed by manipulating on both temperatures as well as on the separation distance. We also learn through this article that the theoretical efficiency established by thermodynamics which is around 80% is far from being reached.

Key words: Thermophotovoltaic, electric power, radiative power, conversion efficiency

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INTRODUCTION

Depending on the distance between the heat source (or emitter) and the thermophotovoltaic cell (TPV), there are two types of TPV conversion [1-5]. We talk about the near-field TPV when the distance is less than the emission wavelength, otherwise it is the far field. Thermally excited electromagnetic waves are of two types, namely progressive waves and evanescent waves [6-11]. However, in the near field the evanescent waves pass the separation medium by radiation tunnel effect in addition to progressive waves. As a result, there is considerable improvement in radiative heat transfer above the black body boundary of Plank. The heat transfer coefficients corresponding to such a distance were three orders of magnitude greater than that of the black body radiation limit. Near field thermophotovoltaic (TPV) has also been studied in the literature theoretically and experimentally. Experimental work has demonstrated the feasibility of near-field TPV with a 10-fold increase in power density and a 30-35% increase in conversion efficiency based on an InGaAs diode of 0.55 eV [12].

THÉORICAL STUDY

Electric power

The maximum electrical power is defined as follows: $P_m = I_m V_m = FF\, I_{ph} V_{oc}$ (1)

The maximum electrical power that can be extracted from the diode is a function of the short circuit current I_{CC} which is equal to the photocurrent (because when $V = 0$, $I_{cc} \approx I_{ph}$), and I_0 is negligible in front of I_{Ph}. Negative influence of a high saturation current on the performance of the thermophotovoltaic cell Indeed, the open circuit voltage V_{co} depends both on the photocurrent and on the saturation current of the diode. The smaller the open circuit voltage, the lower the electrical power extracted.

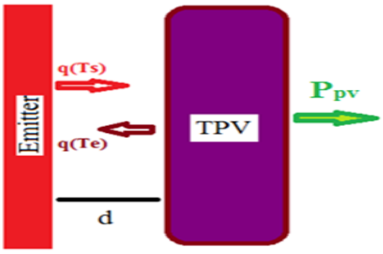

Fig. 1 The different parts of a near-field TPV device

The output power is the important quantity for a system of energy conversion, it is written [14]:

$$P_{PV}(T,d) = \int_{\omega_g}^{\infty} \frac{d\omega}{2\pi} \hbar\omega_0 n(\omega, T_S) K(\omega,d) - \int_{\omega_g}^{\infty} \frac{d\omega}{2\pi} \hbar\omega_0 n(\omega-\omega_0, T_c) K(\omega,d) \tag{2}$$

$$K(\omega,d) = \sum_p \int_{ck \succ \omega} \frac{d^2k}{(2\pi)^2} \Pi_p(\omega,k,d) \tag{3}$$

$$\Pi(\omega,k,d) = \frac{4\,\mathrm{Im}(r_{1p})\,\mathrm{Im}(r_{2p})\,e^{2ik_z d}}{\left|1 - r_{1p} r_{2p} e^{2ik_z d}\right|} \tag{4}$$

$$k_z = \sqrt{\omega^2/c^2 - k^2} \tag{5}$$

The radiative power

The heat source must be well chosen because its wavelengths must be compatible with the material of the TPV cell to hope for a better conversion efficiency. The main one is the offset between the frequency of surface polaritons supported by the hot source and the frequency range of the cell (usually a semiconductor). Indeed, all the photons having an energy higher than the gap frequency are not totally converted into a hole-electron pair, but a part of their energy is dissipated via a phonon excitation. In addition, low energy photons do not contribute to the production of electricity but dissipate in the heat in the atomic network.

The net radiative power in a near-field TPV device is as follows [14]:

$$P_{rad}(d) = \int_{0}^{+\infty} \frac{d\omega}{2\pi} \hbar\omega n(\omega, T_S) K(\omega,d) - \int_{\omega_g}^{+\infty} \frac{d\omega}{2\pi} \hbar\omega n(\omega-\omega_0, T_C) K(\omega,d) \tag{6}$$

$$\omega_0 = \frac{eV_0}{\hbar} \text{ ; with } V_0 = \frac{\hbar\omega_g\left(1 - T_C/T_S\right)}{e} \tag{7}$$

$$\omega_0 = \omega_g\left(1 - T_C/T_S\right) \tag{8}$$

Conversion efficiency

The conversion efficiency is the ratio between the electrical power extracted in the TPV cell by the net radiative power received by the TPV cell. This is an excellent parameter to appreciate the profitability of converting a TPV device. It is defined as follows:

$$\eta_{TPV} = \frac{P_{pv}}{P_{rad}} \tag{9}$$

$$\eta_{TPV} = \frac{\int_{\omega_g}^{\infty} \frac{d\omega}{2\pi} \hbar\omega_0 n(\omega, T_S) K(\omega,d) - \int_{\omega_g}^{\infty} \frac{d\omega}{2\pi} \hbar\omega_0 n(\omega-\omega_0, T_c) K(\omega,d)}{\int_{0}^{+\infty} \frac{d\omega}{2\pi} \hbar\omega n(\omega, T_S) K(\omega,d) - \int_{\omega_g}^{+\infty} \frac{d\omega}{2\pi} \hbar\omega n(\omega-\omega_0, T_C) K(\omega,d)} \tag{10}$$

Upper limit of near field TPV efficiency

Here we are dealing with the upper limit of efficiency for near field thermal radiation that is similar to near-monochromatic radiation treated by thermodynamics [15, 16]. This radiation is largely dominated by the frequency of the resonance mode. That is why this efficiency corresponds to that of a quasi-monochromatic source [15]. We observe the increase in near-field efficiency when the resonant frequency increases but also when the temperature increases. This corresponds to that of near-monochromatic radiation.

$$\eta_{\lim} = 1 - \frac{n(\omega_0, T_e)}{n(\omega_0, T_h)} + \frac{k_B T_e}{\hbar\omega_0} \cdot \frac{m(\omega_0, T_e) - m(\omega_0, T_h)}{n(\omega_0, T_h)} \tag{11}$$

avec m(ω, T) = [1 + n(ω, T)] ln[1 + n(ω, T)] – n(ω, T) ln(ω ,T) (12)

$$n(\omega, T) = \frac{1}{e^{\frac{\hbar\omega}{k_B T}} - 1} \tag{13}$$

RESULTS AND DISCUSSION

Variation of the electrical power

Equation (2) allowed us to realize the curves of Figure 2. In this simulation we considered the temperature of the TPV cell being equal to 300K.

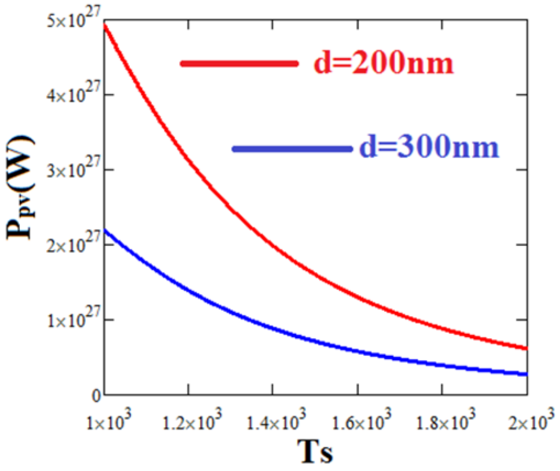

Fig. 2 Electrical output power versus emitter temperature for a constant cell temperature and distance d.

The electrical power extracted by the TPV module decreases exponentially when the temperature of the source increases. Indeed TPV cells are known for their weak gap. These observed temperatures can be adapted to these types of material. The lower the temperature of the emitter, the better. Because high temperatures are detrimental to the survival and durability of TPV panels. The distance between the emitter and the cell plays a vital role in this power. Decreasing this distance clearly increases the power. This is more clearly seen in Figure 3.

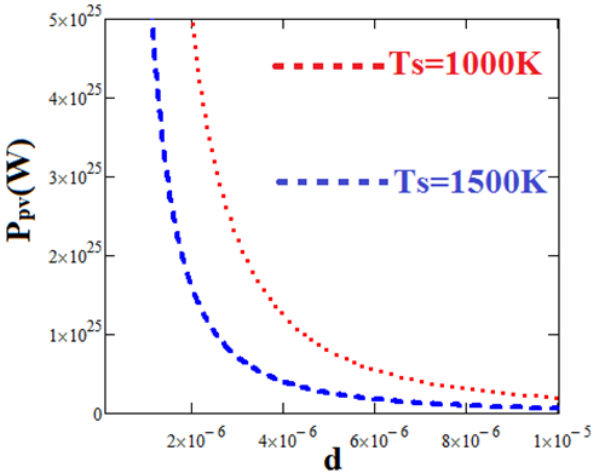

Fig. 3 Electrical output power as a function of distance, d, for a constant temperature of the cell and that of the source

When the distance is reduced, it favors the tunnel tunneling of the evanescent waves which is located at the interface of the emitter and which vanish exponentially. This surplus of energy also causes the growth of the electrical power extracted from the TPV module.

Variation of the radiative power

The radiative power variation coming from the emitter and arriving on the panel is obtained thanks to equation (6). It is represented by figure4. In this figure the variation is studied with respect to the temperature of the emitter. In Figure 5, we study its variation with respect to the distance d.

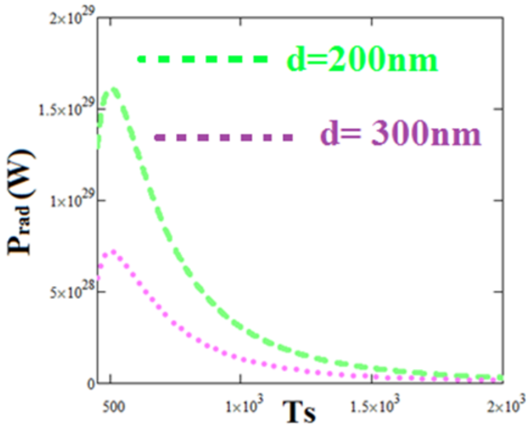

Fig. 4 Variation of the radiative distance according to the temperature of the emitter

It is noted that the radiative power is not favorable to the high temperature of the emitter. The impact is also positive because when a source irradiates a TPV cell, only the wavelengths that correspond to the gap (λ_g)) of the cell material are absorbed. Wavelengths below and above (λ_g) are very degrading to the performance and the TPV device.

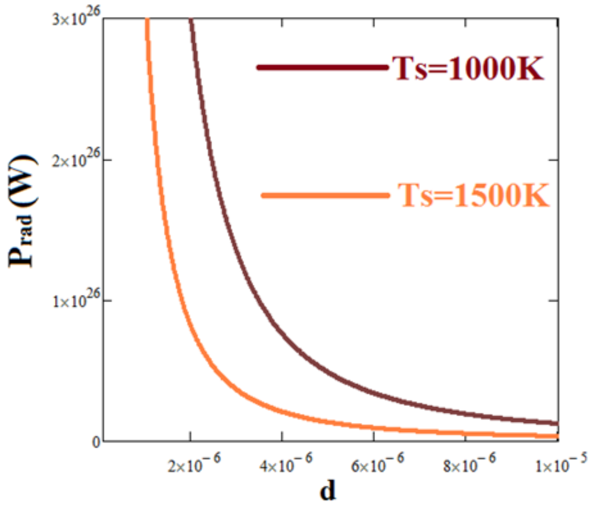

Fig. 5 Variation of the radiative power as a function of the distance d for a constant value of Ts and Tc

What is valid in Figure 3, is also valid in Figure 5 in addition to Figure 4. The radiative power exchanged between the TPV cell and the heat source depends on the distance between them. This is due once again to the contribution of evanescent waves which is confined to the surface of the heat emitter.

Variation in net conversion efficiency

Conversion efficiency is essential to appreciate the quality of a conversion device in general. Equations (9) and (10) allowed us to realize Figures 6 and 7.

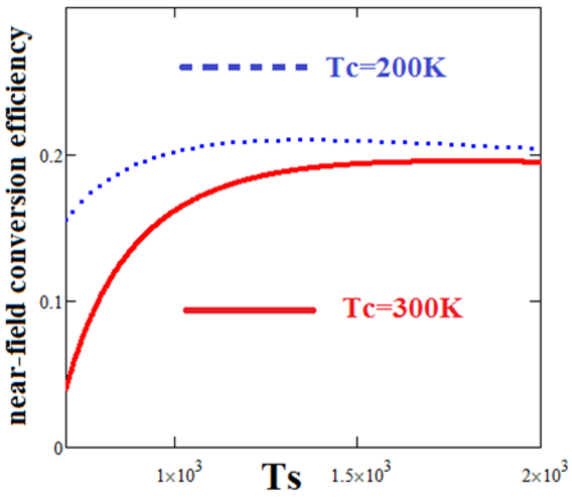

Fig. 6 Evolution of the net conversion efficiency according to the temperature of the source

This efficiency depends strongly on the temperature of the heat source for a constant emitter temperature. The efficiency increases at the same time as the temperature unlike the electric and radiative powers that we studied previously. The powers were not favorable to the high temperatures of the emitter. The efficiency being the ratio of the electric power by the radiative power. Curve 6 tells us that the dependence at low temperatures is more important in the radiative power than in the electric power. This makes the conversion efficiency not dependent on low temperatures. However, these net returns do not exceed 25%.

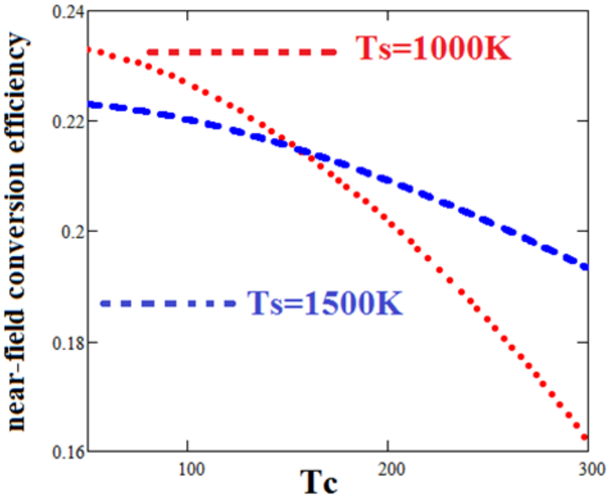

Fig. 7 Net conversion efficiency according to Tc

Keeping the temperature of the source constant, we could realize Figure 7 above. Like the efficiency of Carnot, this efficiency is weakened by the high temperatures of the TPV cell. Indeed, when two bodies are in heat exchange, the amount of heat exchanged is all the more important that the difference in temperature is important.

Limit efficiency between two bodies in near-field heat exchange

This limit efficiency is defined by near-field thermodynamics. This efficiency can be around 80% of the incident radiation. This proves that the net efficiency studied in figures 6 and 7 which is of the order of 25% can be surpassed by improving the heat transfer between the thermal frequency of the evanescent waves and the gap frequency of the cell material.

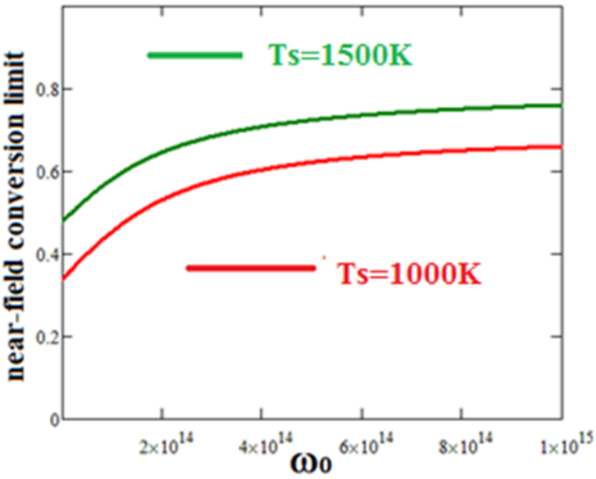

Fig. 8 Conversion efficiency vs resonant frequency

Several methods are proposed to achieve the expected theoretical return. Nowadays graphene is very popular to improve the contribution of phonons and polaritons in heat transfer for its good conversion into electricity.

CONCLUSION

Thermal radiation in the near field promises to give very promising results in the conversion of thermal energy into electricity. Its theoretical net return is of the order of 24%. We have seen that we can raise a few units just by keeping the temperature of the cell very low. This gives a spot for research on the refrigerant system that can solve this problem. Even if this conversion efficiency is very low compared to the theoretical yield established by the near-field thermodynamics which is of the order of 80% of the incident radiation. This proves that there is still a major task to be accomplished in all parts of the near field TPV device.

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