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Overview and Status of Thermophotovoltaic Systems

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Abstract

In the last decade thermophotovoltaic (TPV) generator has gained an increasing attention as cogeneration system for the distributed generation sector. Nevertheless, these systems are not fully developed and studied: several aspects need to be further investigated and completely understood.
The aim of this study is to give a complete overview and the status of the art of thermophotovoltaic generation considering both the research developments and the experiences field. More in details, in this study, the characteristics of a TPV generator are analyzed with a particular attention to the physical relationships which govern the behavior of its main components. Moreover, the current technologies regarding the combustor, the emitter, the optical filter and the photovoltaic cells are investigated by taking into account both the role of each component and also their integration in the whole system. Finally, a critical review of the realized prototypes is presented and discussed.

Keywords: Thermophotovoltaic generator, state of the art, analytical aspects, review.

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1. Introduction

A Thermophotovoltaic generator (TPV) is an innovative system able to convert the radiant energy of a combustion into electrical energy. This conversion is realized by using photovoltaic cells. A scheme of a TPV is presented in Figure 1, in which the main components and energy flows are highlighted.

A TPV generator consists of a heat source, an emitter (EM), a filter (F) and an array of photovoltaic cells (PV); the combustion air pre-heating system (HX-A) which uses the combustion products is also sketched in Figure 1. The thermal production of the TPV is realized by the heat exchangers HX-PV and HX-CP, which respectively recover the heat from the cooling of PV cells and the exhaust combustion products.

The main advantages of this energy system can be found in the (*i*) high fuel utilization factor (close to the unity thanks to the recovery of the most of the thermal losses, making it possible to use the TPV system as a combined heat and power system), (*ii*) low produced noise levels (due to the absence of moving parts), (*iii*) easy maintenance (similar to a common domestic boiler) and (*iv*) great fuel flexibility. In fact, with this regard, it can be observed that the heat source of a TPV system can be provided by various fuel typologies such as fossil fuels (natural gas, oil, coke, etc.) municipal solid wastes, nuclear fuels, etc; concentrated solar radiation can also be used as a TPV heat source [1-3]. A TPV system usually allows very low pollutant emissions (e.g. CO and NOx), since it is often coupled with combustion devices such as domestic boilers.

The main use of a TPV generator can be in the distributed combined heat and power generation, but its application in the automotive sector in case of hybrid vehicles [4], glass [5] or other high temperatures industries [6] has also been analyzed in literature. The TPV system has been proposed for portable generators [7, 8], co-generation systems [9], combined cycle power plants, solar power plants [10], grid connected [11] or independent equipment [12]. Other studies show the integration of TPV generator with thermoelectric systems [13] or with Organic Rankine Cycles [14, 15]. Further studies were developed in military [16-17] and space [18, 19] sectors.

Even if the first studies [20, 21] about thermophotovoltaic conversion were carried out during the early years of 1960, it was only in the last decade that the research about TPV generation accelerated markedly. The electrical efficiency of the realized prototypes [19, 22-27] ranges from about 0.6 % to slightly less than 11.0 %. Moreover, electrical efficiencies close to 24 % are predicted in literature [28-30], making TPV system very attractive for cogeneration. An overview about the realized TPV generator prototypes will be developed in this work.

2. Electrical performance of a TPV generator

The power balance of a TPV generator is presented in Figure 2. The introduced power with fuel (P_{in}), unless the thermal losses ($P_{fuel,loss}$) of the combustion process, is converted by the emitter and by the optical filter into radiant power ($P'_{GAP} = P_{RAD} - P_{back}$) and thermal power discharged with the gases ($Q_{TH,gas}$ in Figure 2 and section F_2 in Figure 1). A fraction of the radiant power (P'_{GAP}), which is in the useful range of wavelengths for the photovoltaic conversion (due to the optical filter selection), can be lost due to the absorption of the optical filter (P_{abs}, even if this term can be usually neglected) and for the view factor between filter and PV cells (P_{loss} this term can be reduced achieving values very close to zero with a optimal design of the system geometry). The radiant power incident on the photovoltaic cells ($P_U = P_{GAP} - P_{loss} = P'_{GAP} - P_{loss} - P_{abs}$) is then converted into continuous current ($P_{el,dc}$) and thermal power ($Q_{th,pv}$); except for the losses ($P_{el,loss}$) due to the inverter (INV in Figure 1) efficiency, the electrical power ($P_{el,ac}$) can be obtained from the system. On the other hand, the enthalpy content of the gases at the emitter exit ($Q_{TH,gas}$ in Figure 2 and section F_2 in Figure 1) can be partially recovered ($Q_{TH,cp}$) while the remaining part is discharged to the ambient ($Q_{th,d}$).

The electrical efficiency of a TPV generator can be written as:

$$\eta_{EL,TPV} = \eta_{CC} \cdot \eta_{RAD} \cdot \eta_{GAP} \cdot \eta_F \cdot \eta_{VF} \cdot \eta_{PV} \cdot \eta_{dc/ac} \cdot$$

where: η_{CC}: combustion efficiency; η_{RAD}: radiant efficiency; η_{GAP}: spectral efficiency; η_F: filter efficiency; η_{VF}: view factor efficiency; η_{PV}: cell efficiency $\eta_{dc/ac}$: inverter efficiency.

On the following of this section each of the previous partial efficiencies will be separately analyzed and discussed.

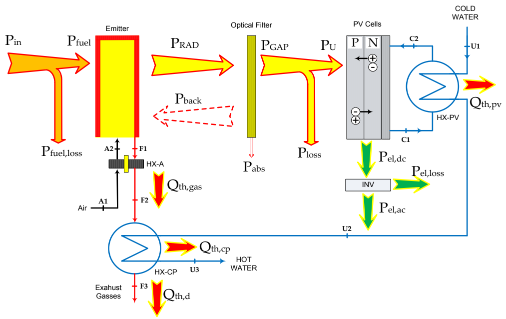


Fig. 1. Schematics of a TPV generator

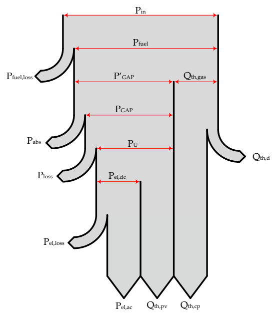


Fig. 2. Power balance of a TPV generator

2.1. Combustion efficiency

With reference to Figure 2, the *combustion efficiency* can be expressed as the ratio between the useful introduced power (P_{fuel}) and the whole power introduced with fuel (P_{in}):

$$\eta_{CC} = \frac{P_{fuel}}{P_{in}} = \frac{P_{fuel}}{\dot{m}_{fuel} \cdot LHV}$$

being $\dot{m}_{fuel}$ and LHV respectively the fuel mass flow rate and its Lower Heating Value (depending on the type of fuel).

From Figure 2, it can be observed that the useful introduced power (P_{fuel}) can be only converted into radiant power ($P'_{GAP} = P_{RAD} - P_{back}$) or discharged with the combustion products ($Q_{TH,gas}$). It results:

$$P_{fuel} = P'_{GAP} - Q_{TH,gas}$$

This last equation represents the power balance of combustor, emitter and air pre-heater exchanger and allows to introduce the important role recovered by the air pre-heater for the thermophotovoltaic conversion. In facts, the reduction of combustion products temperature (section F2 in Figure 1) and then the increase of the air temperature upstream of the combustor (section A2 in Figure 1) allows to enhance the emitted radiant power; this evidence is also confirmed in [31]. The importance of air pre-heater has been also highlighted in Seal et al [32], and Christ et al [33]. In particular, in Colangelo et al [29] the air pre-heater was obtained by adopting a rotary heat exchanger with a ceramic material which is lighter than metal and with a greater heat capacity that is relevant to store an high value of energy; with this device an heat exchanger efficiency greater than 75% is achieved.

2.2. Radiant efficiency

The *radiant efficiency* can be expressed, with reference to Figure 2, as the ratio between the radiant power from the emitter (P_{RAD}) and the introduced power (P_{fuel}) into the system. It follows:

$$\eta_{RAD} = \frac{P_{RAD}}{P_{fuel}} = \frac{p_{RAD} \cdot S_{em}}{\eta_{CC} \cdot \dot{m}_{fuel} \cdot LHV}$$

The radiant power is a function of the radiation power density p_{RAD} and of the emitter surface S_{em}. The radiation efficiency is strictly influenced by several factors: the type of emitter, its dimension and thickness, the combustion mode, the firing rate and, as already seen, the pre-heating of the air.

It can be observed that the radiant energy density can be up to 500 kW/m^2 (by integrating the spectrum of a black body at 1600 °C). This last value is very high considering that the radiant energy density of the sun is equal to 1 kW/m^2 at AM1.5 condition. The achievement of high temperature is a very important aspect since, according to Planck's law, radiation power density scales with temperature to the fourth power. Therefore, most heat sources used in TPV systems are based on combustion systems; various types of *premixed* and *non-premixed* combustors [34-36] or radiant tube burner [37, 38] have been developed in the last years. It should be considered that the aim toward high temperatures burner is limited by the NOx production. Anyway, recent studies [39, 40] about the emitter surface have shown that there exist an optimal value of emitter surface which allows the maximization of radiant efficiency and of emitter temperature been equal the boundary conditions (such as introduced power with fuel, emitter material, etc.) and the adopted equipment of the thermophotovoltaic generator.

The radiant energy from the emitter has to be characterized by an emission spectrum suitable for the adopted photovoltaic cells; in fact only the photon energy in a narrow band above the bandgap of the photovoltaic cells can be converted into electrical energy. It follows that selective emission is required; in order to achieve this goal a *selective emitter* [39-49] or a *broadband emitter* with a filter can be used. In the first case the emitter is made with materials such as rare earth oxides which are characterized by an emission spectrum centered on specific wavelength; in the second case, many of the emitted photons, due to their lower energy on the respect of the bandgap of photovoltaic cells result unusable. It is imperative to send these photons back to the radiator in order to conserve heat and to reduce the fuel consumption needed to achieve the required emitter temperatures.

It should be observed that the material used for the emitter needs to have specific characteristics such as (*i*) thermal stability, (*ii*) corrosion resistance, (*iii*) shock resistance, (*iv*) high thermal conductivity, etc. Obviously, the high temperatures which are required by the TPV system implies that the emitter's material melting point should be as high as possible. Further, the emitter needs to be thermally stable in the selected atmosphere (i.e. air and/or combustion products) and high corrosion resistant; as example graphite (C) has a high-thermal conductivity and a good thermal shock but in an oxidizing atmosphere cannot overcome 400 °C [50]; on the contrary in non-oxidizing atmosphere can operate up to 3000 °C. The adoption of coatings can improve the corrosion resistance of some materials or a shield, usually made of quartz, can be adopted to protect the emitter from the environment. A high value of thermal conductivity is required in order to have a uniform temperature distribution of the emitter. Lower values of thermal conductivities causes a large temperature gradient inside the emitter which drastically decreases its efficiency. Anyway, in case of porous emitter this factor may not be important. Thermal shock resistance is also very important especially in TPV generators with frequent on-off cycles. The sudden change in emitter temperature can cause material failure.

High temperature broadband emitters [51-57] can be divided into (*i*) oxide based or (*ii*) non-oxide based ceramics. Among oxide based ceramics, alumina (Al_2O_3) and zirconia (ZrO_2) show a good stability in oxidizing atmosphere and can be used respectively up to 1900 °C of temperature or more considering that their fusion temperatures are respectively 2050 °C and 2600 °C. Others oxide based ceramics are magnesia (MgO), silica (SiO_2), beryllia (BeO), hafnia (HfO_2), thoria (ThO_2) and yttria (Y_2O_3) [51]. Anyway, often the major difficult related to the adoption of these materials is the low thermal shock resistance and/or the low emissivity.

A widely used broadband emitter is silicon carbide (SiC) which can operate up to 1650 °C. It has an emissivity close to 0.90 [56] and very high melting point. Ceramic composites such as SiC/Si and SiC coated ceramic composites fit all the requirements for a TPV emitter [57].

2.3. Spectral efficiency

The *spectral efficiency* is the ratio between the whole radiation from the emitter (P_{RAD}) and the portion which pass through the filter (P'_{GAP}):

$$\eta_{GAP} = \frac{P'_{GAP}}{P_{RAD}}$$

The spectral efficiency depends on the adopted filter, used to match the emitter spectral emission to the PV cell; this means that the filter should be ideally able to block all the photons with energy lower than the PV cell bandgap and pass the photons with higher energy. With a simple approach, the P'_{GAP} can be estimated by integrating the radiant intensity $I(\lambda;T_{em})$ in the range of wavelengths (from 0 to λ_{GAP}) which passes thought the filter and then can be converted by the photovoltaic cells:

$$P'_{GAP} = \varepsilon \cdot S_{em} \int_0^{\lambda_{GAP}} I(\lambda;T_{em}) \cdot \tau(\lambda)\, d\lambda = \varepsilon \cdot S_{em} \int_0^{\lambda_{GAP}} \frac{2\pi c^2}{\lambda^5} \left[\exp\left(\frac{hc}{\lambda k_B T_{em}} \right) - 1 \right]^{-1} \cdot \tau(\lambda) d\lambda$$

Many types of filters have been developed such as plasma filters, 1-D photonic bandgap filters, 2-D photonic bandgap filters, 3-D photonic bandgap filters, combination of plasma filter and 1-D photonic bandgap filter, dielectric stacks or back-surface reflectors [58-69].

3-D photonic bandgap filters are characterized by an omnidirectional photonic band gaps which means that the propagation of photons is prohibited for arbitrary polarization in any direction [69]; obviously, this characteristic is highly appreciated for TPV generation. Anyway, it should be observed that a well designed 1-D photonic bandgap filter can completely reflect polarized photons at all incident angles showing omnidirectional photonic band gaps [65, 68]. On this regards, filters based on multiple layer of SiO_2 [62-65] have shown promising results for TPV applications.

2.4. Filter efficiency

The *filter efficiency* takes into account the fraction of radiant power which is absorbed by the filter (P_{abs}) and which is lost. The filter efficiency can be written as:

$$\eta_F = \frac{P_{GAP}}{P'_{GAP}}$$

being the balance of the filter ($P_{RAD} - P_{back} = P'_{GAP} = P_{GAP} + P_{abs}$). Usually the term P_{abs} can be neglected with a properly design of the filter and then it is possible to assume $\eta_F = 1$ [65].

2.5. View factor efficiency

The *view factor efficiency* is related to the ratio between the radiation (P_U) which is incident on the photovoltaic cells and the value (P_{GAP}).

$$\eta_{VF} = \frac{P_U}{P_{GAP}}$$

The value of view factor can be calculated according to the geometry and to the distance among the surfaces which are involved in the irradiation phenomenon. Many formulations of radiation view factors can be found in literature on the basis of the TPV geometry [71-76].

2.6. PV cells efficiency

The *cells efficiency* represents the ratio between the electrical power output ($P_{el,dc}$) and the incident power on the cell (P_U); the maximum electrical power produced by a photovoltaic cell can be expressed as function of short-circuit current (J_{SC}) open-circuit voltage (V_{OC}) and Fill Factor (FF). The radiation efficiency is influenced by many factors such as the cell material, the emitter temperature and the radiation intensity. It can be expressed as follows:

$$\eta_{PV} = \frac{P_{el,dc}}{P_U} = \frac{V_{OC} \cdot J_{SC} \cdot FF}{P_U}$$

Converters for TPV are very similar to standard solar cells such as Si and high efficiency GaAs but made of semiconductor materials with lower bandgap, to get a better spectral matching with the emitter radiation.

A fundamental parameter in order to estimate the conversion efficiency of a PV cell is the external quantum efficiency $EQE\ (\lambda)$ which can be defined as the probability that a photon of wavelength λ will be absorbed by the cell, generating an electron that will be collected at the terminals: it considers the reflection and absorption of incident photons and the generation/collection of minority carriers, so it describes the behavior of the p-n junction in great detail.

The actual value of J_{SC} produced by the cell can be calculated from $EQE(\lambda)$ of the PV cell and the incident photon flow $\Phi(\lambda)$:

$$J_{SC} = e \int_0^{\lambda_{GAP}} \Phi(\lambda) \cdot EQE(\lambda) \cdot d(\lambda)$$

EQE(λ) were measured for different semiconductors of choice for TPV and typical behaviours are reported in Figure 6 [84-88]. It could be noted that most of the materials used for the TPV cells have high *EQE* in a large region from near the bandgap to lower wavelength. The *EQE* drops to very low value for photon wavelength of about 1000 nm, but it should be considered that in this region a standard TPV emitter at 1200-1800 °C has a very low photon emission. For this reason, the TPV cells are usually able to convert with a very high efficiency the part of the black body radiation that arrives at their surface, while the photons with energy lower than the bandgap, not being absorbed, can be effectively redirected towards the emitter with the use of appropriate selective filters. This particular characteristic, not possible for solar PV, permits TPV cells to potentially reach very high conversion efficiencies, because the incident radiation could be efficiently coupled to the region where the cell *EQE* is maximum.

2.7. Inverter efficiency

Finally, the *inverter efficiency* allows the calculation of the final electrical output of the system. It results:

$$\eta_{dc/ac} = \frac{P_{el,ac}}{P_{el,dc}}$$

Useful information about the efficiency of inverter adopted with PV cells can be found in [89]. In particular it can be observed that the use of transformer usually reduces the conversion efficiency from direct current to alternate current.

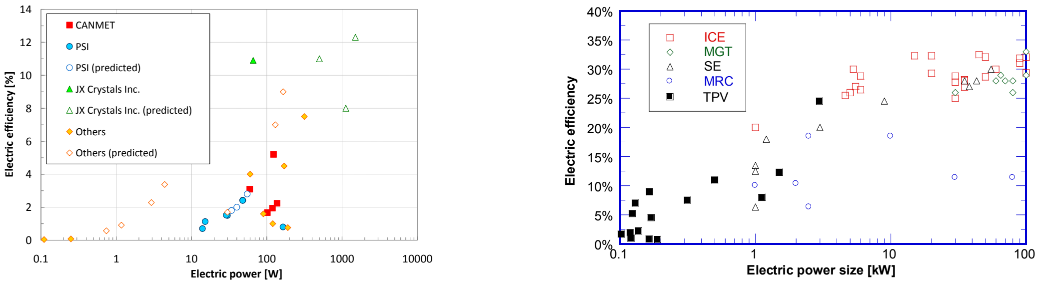
3. TPV PROTOTYPES

Various TPV prototypes have been realized in the last years; the most relevant research groups on this topic are the CANMET Energy Technology Centre, the Paul Scherrer Institut, and the JX Crystals Inc [90-92]. The main results show electrical efficiency from 0.04% up to more than 24% [90-92]; with regards to the produced electrical power, values ranging from less than 10 W to about 3 kW are reported in literature [90-92]. In Figure 3 (a), the electrical efficiency of the realized prototypes versus the electrical power output is presented [90-92]; in Figure 3 (b) the same performance vales of the realized prototypes are compared to conventional CHP systems. In particular, from this last figure it can be observed that TPV can cover the field of electrical power output lower than 1-2 kW showing a conversion efficiency close to 10%.

All the data available in literature regarding the TPV generator are presented in Table 1, for all the main components of the TPV unit (burner, emitter, filter, cells). Table 2 reports the type of fuel, the emitter material, its structure, the surface temperature and the emitter radiation efficiency, the presence or absence of the filter and its material, the type of cells and their efficiency at Standard Test Condition (STC - AM 1.5, 100 mW/cm^2). The last column states whether the performance comes from an experimental measurement or if it is predicted by using a numerical model. Therefore, Table 1 provides a synoptic view of the state-of-the-art technological level of TPV systems and also envisions possible future pathways for research and development of TPV systems.

Tab. 1. Summary of TPV prototypes

Burner	Emitter	Type of emitter	Surface emitter temp.	η_{rad}	Filter	Cells	STC eff.	P_{fuel}	P_{el}	η_{el}	Type of result
			[K]	[%]			[%]	[W]	[W]	[%]	
butane gas	Yb_2O_3	fibrous mantle			no	Si	10.4	305	0.11	0.04	EXP
butane gas	Er_2O_3	fibrous mantle			no	GaSb		305	0.25	0.08	EXP
hydrogen	SiC		1265		no	GaSb		130	0.74	0.57	PRED
	Yb_2O_3-coated Al2O3	foam ceramic				Si		2000	14	0.70	EXP
	Yb_2O_3					Si		25000	190	0.76	EXP
methane	Yb_2O_3				quartz tube	Si	16.0	20000	164	0.82	EXP
hydrogen	SiC		1265		no	GaInAs Sb		130	1.2	0.91	PRED
methane	Yb_2O_3		1800	24.0	quartz tube	Si	16.0	12000	120	1.00	EXP
butane	Yb_2O_3	spherical emitter				Si		1350	15	1.13	EXP
	Yb_2O_3	fibrous mantle				Si		2000	30	1.50	EXP
butane	Yb_2O_3				glass tube	Si	16.0	1905	29	1.52	EXP
	Yb_2O_3					Si		5625	90	1.60	EXP
	Sic	coated fiber mat		20.4		GaSb	20.0	6120	102	1.67	EXP
butane	Yb_2O_3				glass tube	Si	16.0	1905	34	1.80	PRED
	Sic	honeycomb plaque		22.9		GaSb	20.0	6120	119	1.94	EXP
	Yb_2O_3	fibrous mantle			TCO	CuInSe 2 (CIS) thin-film		2000	40	2.00	PRED
	SiC	porous foam		26.7		GaSb	20.0	6120	137	2.24	EXP
hydrogen	Co/Ni-doped MgO				no	GaInAs Sb		130	2.9	2.28	PRED
butane	Yb_2O_3	porous foam	1735		SnO_2 film on quartz	Si		1980	48	2.42	EXP
butane	Yb_2O_3				glass tube	Si	21.1	1985	48	2.41	EXP
butane	Yb_2O_3				glass tube	Si	21.1	1985	55	2.80	PRED
	(1) Yb_2O_3 fiber felt; (2) SiC-coated ceramic fiber mat	Two emitters arranged in tandem		31.0		Si GaSb	36.0 20.0	1920	60	3.09	EXP
hydrogen	Co/Ni-doped MgO				no	GaSb		126	4.4	3.48	PRED
			2000					3778	170	4.50	EXP
	SiC	porous foam	1558	21.3	coatings of SiO2 and TiO3 on glass	GaSb		8260	123	5.20	EXP
			2100					4200	315	7.50	EXP
	SiC				double quartz tube	GaSb		14000	1120	8.00	PRED
regenerative burner	AR-coated tungsten (W) foil on Alumina				dielectric filters	GaSb		606	66	10.90	EXP
	AR-coatet tungsten (W) foil on SiC		1525			GaSb		12200	1500	12.30	PRED
diesel	SiC-caoted ErAG		1523		quartz tube	AlGaAs / GaAs		12157	2976	24.50	PRED



(a) (b)

Fig. 3. (a) electric efficiency vs. electric power of TPV prototypes, (b) comparison of TPV performance to conventional system [92, 94]

4. Concluding remarks

The thermophotovoltaic conversion has gained more and more attention in the last decade. Nevertheless this field of the research is not yet completely understood.

This paper wish to outline the current state-of-the-art of thermophotovoltaic generation under both the analytical and the experimental point of view.

More in details, in this study a deeply investigation of all the analytical aspects which involve the thermophotovoltaic conversion is presented; each term which composes the conversion efficiency between the introduced power with fuel and the produced electrical output is investigated. All the components which compose a TPV generator are investigated in terms of adopted materials and engineering solutions. Further a comprehensive review of all the prototypes developed up to now is reported and analyzed.

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