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Jarosław TATARCZAK[1]
Jarosław SIKORA[2]

THE USE OF THERMIONIC EMISSION PHENOMENON AS SUPPORT FOR RENEWABLE ENERGY SOURCES

Energy converters using the phenomenon of thermionic emission to generate electricity and their applications related to renewable energy sources (RES) have been presented. Taking into account new technical solutions, hybrid systems combining thermionic energy converters (TEC) with other energy generators, e.g. with PV cells, the Stirling engine, improving the efficiency of the entire electric energy generating system, have been described. Leading technologies related to thermionic energy conversion and TEC hybrid systems powered by solar radiation have been shown in the tables. The dynamic development of TEC technology in recent years, in our opinion, will contribute to the wider interest of research communities to use the thermionic emission phenomenon to generate electricity.

Keywords: thermionic emission, renewable energy sources, thermionic energy converters, hybrid systems, electric energy

1. Introduction

Renewable energy sources already were used by humans thousands of years ago for example to mill grain, allow traveling across the sea using to the strength of the wind. Over time, the importance of machinery increased, that were powered by the energy of water and wind movement [1]. In the industrial era many new technical solutions were created. In 1747, the French astronomer Jacques Cassini developed a solar furnaces, which was able to get the temperature above 1,000ºC. Then, in 1773 another French scientist Antoine Lavoisier obtained a temperature allowing melting of iron (above 1,500ºC). Currently, solar furnaces are able to heat, using a focused beam of sunlight, a given material up to a temperature of 3,000ºC [1, 2].

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[1] Corresponding author: Jarosław Tatarczak, Politechnika Lubelska, Katedra Automatyki i Metrologii, ul. Nadbystrzycka 38A, 20-618 Lublin; jaroslaw.tatarczak@gmail.com

[2] Jarosław Sikora Politechnika Lubelska, Katedra Automatyki i Metrologii, ul. Nadbystrzycka 38A, 20-618 Lublin; tel. 81 538 43 04; jaroslaw.sikora@pollub.pl

During the intensive development of the industry (at the turn of the 17th and 18th centuries), the demand for fossil fuels (coal or oil) increased which were used by steam engines and then by combustion engines. At that time, an innovative technical solution emerged that was associated with the conversion of thermal energy directly into mechanical energy. It was a thermal engine created by Robert Stirling, patented in 1816 (Patent No. 4081). Currently, this engine can be powered by burning fossil fuels, using waste heat or by solar energy.

The photovoltaic phenomenon was first observed in 1839 by Alexandre Edmond Becquerel (the father of the future Nobel laureate in physics - Henri). He noted rise in electrical current as a result of a chemical reaction induced by sunlight [3]. This technology did not find a wider application until 1954 when the first photovoltaic (PV) module was developed in the Bell Laboratory for the space programs.

Due to the lack of oxygen in the orbital space, fuel combustion is not possible (or very complicated). Space programs have caused intensive development of converting thermal energy into electricity using thermionic emission powered by radioactive decays energy [6].

The phenomenon of thermionic emission has been studied since the late nineteenth century. In 1873, British scientist Frederick Guthrie observed that the red-hot iron ball in air could retain a negative charge [5]. Then in 1885, American inventor Thomas Edison observed the flow of electric current between hot and cold electrodes placed in a vacuum. Owen Richardson determined the relationship between the thermionic electron current density and the work function and the temperature of the cathode [5]:

$$J = A \cdot T_C^2 e^{-\varphi_C / kT_C} \tag{1}$$

where: A is the Richardson's constant, T_C is the cathode temperature, ϕ_C is the cathode work function, k is the Boltzmann's constant.

A device implementing energy conversion method using thermionic emission was called the thermionic energy converter (TEC) and was one of the first that directly converted thermal energy into electricity.

2. Analysis of TEC technology

TEC technology is divided into: vacuum (VTEC) and vapour (e.g. caesium) converter. An example of output current-voltage characteristic of VTEC, determined for $T_c = 1{,}200\,\mathrm{K}$, $T_a = 300\,\mathrm{K}$, $\varphi_c = 1{,}8\,\mathrm{eV}$, $\varphi_a = 1{,}2\,\mathrm{eV}$, $d = 10\,\mu\mathrm{m}$, is presented in Fig. 1.

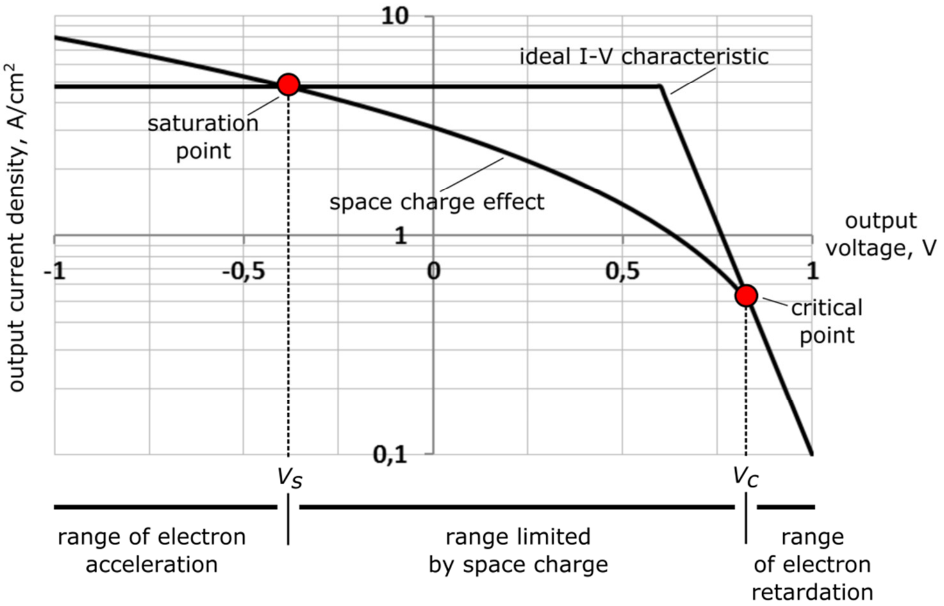

Fig. 1. An example of output current-voltage characteristic of TEC. V_s is saturation voltage, V_c is critical voltage

It is seen from this figure that the space charge decreases the output current density in respect to the ideal I-V characteristic. The main task of caesium vapour is to lower the work function of the cathode and reduce the effect of space charge [7]. The efficiency of the tested TEC converter was within the range of $(0.5 \div 15.1)\%$, with maximum power densities: $(0.2 \div 6)$ W/cm^2 [12].

Many technical solutions have been created, which were often combinations of TEC and an additional structural element. A list of leading technologies is given in the table below.

Table 1. Leading technologies related to thermionic energy conversion

Short name	**Full name**	**First written references**	**Compatibility with RES**
VTEC	vacuum thermionic energy converter	1959 [10]	✓
-	vapor thermionic energy converter	1962 [7]	✓
MTC	microminiature thermionic converter	2000 [9]	✓
PETE	photon-enhanced thermionic emission	2010 [10]	✓
NETEC	near-field enhanced thermionic energy conversion	2017 [11]	✓

The global trend towards miniaturization, also affect the development of technology TEC. In 2001, a microminiature thermionic converter (MTC) was patented. Reducing the distance between the electrodes limits the distance that electrons must overcome. This has a positive effect on the efficiency of TEC. The temperature of the proposed solution should be between 530 and 1,030ºC. Despite the promising model efficiency of 15÷25%, these values have not been achieved [8].

In 2010, a new phenomenon of photon-enhanced thermionic emission (PETE) was described [10]. PETE converter powered by sunlight gives the theoretical efficiency at: 11.2÷48.6%. However, assuming that an additional work cycle (e.g. Stirling engine) is connected to the PETE converter, the overall efficiency could be as high as 70.4% [12].

In 2017, for generating electric energy a near-field enhanced thermionic energy conversion was proposed [11].

3. Renewable energy sources and thermionic emission

Renewable energy sources are often related to a multi-stage energy conversion. For example, the difference in pressure in the atmosphere causes the air movement which powers the blades of the turbine, changing| the wind kinetic energy into the mechanical energy. This energy is then converted by electric generator for electricity. A similar situation occurs in the case of hydroelectric power plants which use potential and kinetic energy of water to power generation. Water that falls on the water turbine blades rotates the electric generator's rotor, thus generating electrical energy.

The use of biomass also requires the conversion of energy in many stages. In order to release the chemical energy accumulated in plants, they should be burned or gasified. The further stages of converting thermal energy is analogous to solutions in fossil fuel power plant. In such power plants, fuel (e.g. coal) is burned in the furnace and heats the water. Further, water is converted to steam. Then as a result of the pressure difference (compression and later condensation), it moves and rotates the steam turbine blades. Steam turbine drives a generator to produce electricity. This water cycle in a closed system is called the Rankine cycle. For gases, the Brayton-Joule cycle is the same process.

The above examples prove that the processes of energy conversion from RES are often multi-stage. Each stage has a certain efficiency of converting energy into another form. A solar radiation conversion into electricity has two important features. The first feature is the possibility of direct conversion of solar radiation into electricity (using, for example, photovoltaic cells). Consequently, the second feature is the lack of necessity to use moving parts.

Hybrid solutions combine several devices with different properties to improve the efficiency of the entire system. At each energy generation stage electricity would be obtained. For example, heat is supplied to the thermionic energy converter (by solar radiation or biomass burning), resulting in electricity generation. Then wasted heat (from TEC) powers the next energy conversion stage, for example, Rankin cycle or Stirling engine.

4. TEC-RES hybrid systems

Thermionic energy converters are powered by heat. Heat sources (>1,000ºC) associated with RES require some technical solutions to concentrate energy. They can be divided into solutions: related to the combustion of biomass and the concentration of solar radiation. The last solution can be divided into five main categories of solar concentrators: heliostat field reflectors, parabolic dish reflectors, parabolic trough reflectors, linear Fresnel reflectors and Fresnel lenses [12].

Systems powered by solar energy are the most ecological solutions because they do not produce any greenhouse gases. The table below presents hybrid solutions of TEC devices powered by solar radiation.

Table 2. TEC hybrid systems powered by solar radiation

Short name		**PETE**	**TIPV**	**NETEC**
Full name		photon-enhanced thermionic emission	thermionic-photovoltaic converter	near-field enhanced thermionic energy conversion
An additional phenomenon		photoemission	photovoltaics	near field thermal radiation
The possibility of an additional cycle		Stirling engine, Rankin cycle	no data in the literature	no data in the literature
Max. efficiency	1,000ºC	41% $^{a)}$	55%	39%
	1,200ºC	45% $^{b)}$	52%	40%
Max. power density	1,000ºC	no data in the literature	1 W/cm^2	0.5 W/cm^2
	1,200ºC	no data in the literature	1.3 W/cm^2	1.05 W/cm^2
Literature (year)		[13] (2016)	[14] (2016)	[11] (2017)

Concentration of sunlight: $^{a)}$ x225 $^{b)}$ x1000

The technologies presented above have a diverse structure. The PETE converter, presented in Fig. 2a, uses at least two electrodes for converting solar radiation into electricity. Advanced solutions use a multi-junction system with different cathodes increasing the efficiency of the entire system, due to the more efficient conversion of selected wavelengths of solar radiation [13].

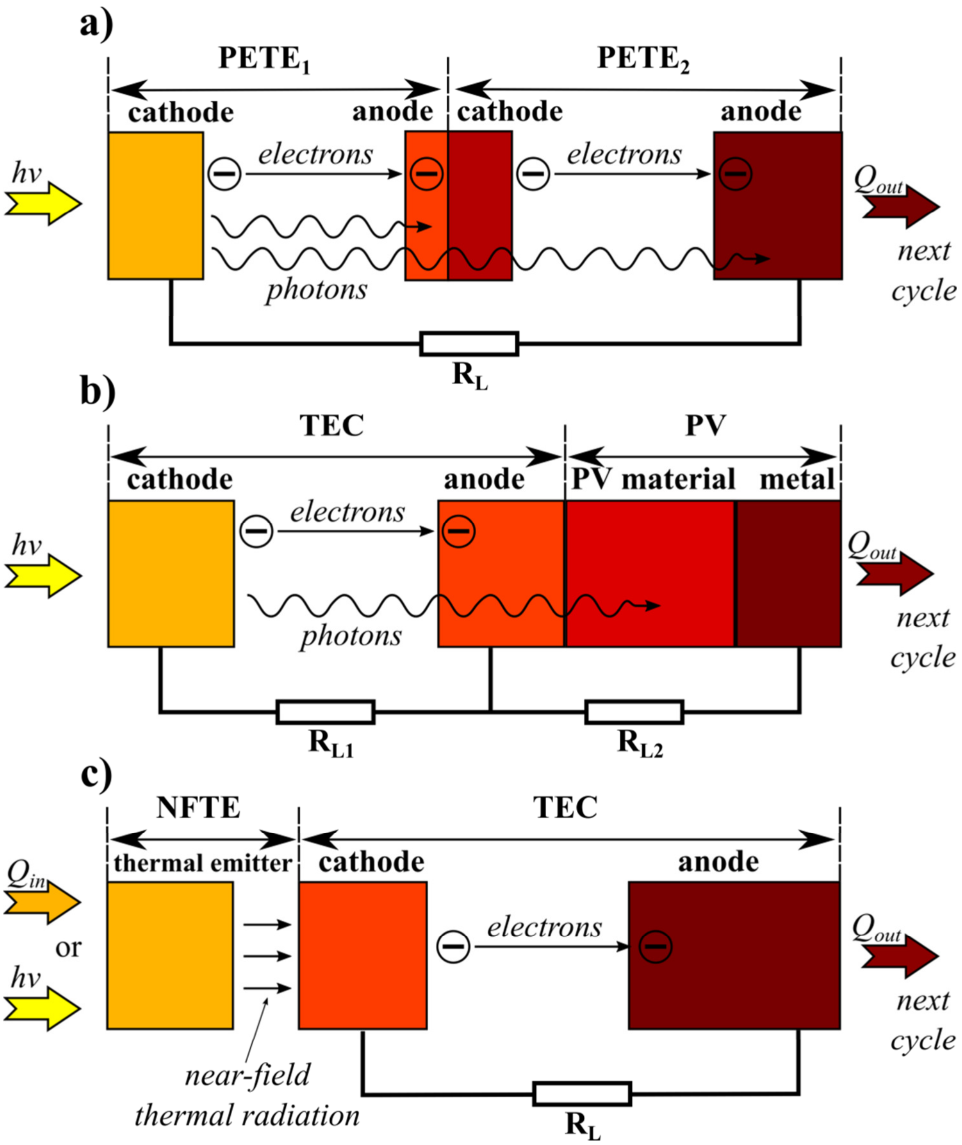

Fig. 2. Simplified diagrams of hybrid TEC technologies: a) PETE converter with a two-junction system [13], b) Thermionic-photovoltaic converter [14], c) TEC powered by a near field thermal radiation (NETEC [11]). R_L, R_{L1}, R_{L2}, are load resistor, Q_{in} is the input heat, Q_{out} is the output (wasted) heat, $h\nu$ is the energy of light quantum

Thermionic-photovoltaic converter (Fig. 2b), used features of the thermionic emission and photovoltaic phenomenon, was proposed in 2016. A transparent anode (with low work function) of the TEC is connected to the PV converter. The PV material is GaSb or InGaAs. In the back of the TIPV, a metal reflector reflects the high energy photons back to the PV layer. The anode and PV layer are maintained at a temperature of about 300K [14].

The next hybrid converter uses phenomenon occurring at the nano scale, so-called a near-field thermal radiation. A simplified diagram of the near-field enhanced thermionic energy converter (NETEC) is presented in Fig. 2c. It contains a thermal emitter which is separated from the cathode by a distance smaller than the radiation wavelength (less than 100 nm) which allows to generate ten times more electricity at a given temperature with respect to TEC type converters [11].

5. Conclusion

In relation to electricity generation, the phenomenon of thermionic emission over a long period of time was studied only by a small group of researchers, in compared to the photovoltaic phenomenon. The recent development of technology, including the emergence of new materials and technologies at the micro scale (MEMS), has contributed to the wider interest of research communities to use the thermionic emission phenomenon to generate electricity.

Currently, an important goal is, among others, to combine thermionic energy converters with other energy generators, e.g. with PV cells, the Stirling engine because hybrid solutions can significantly improve the efficiency of the entire electricity generating system powered by renewable energy sources.

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