REVIEW OF THE DEVELOPMENT OF THERMOPHOTOVOLTAICS

Surya Narrayanan Muthukumar[1], Krishnar Raja[2], Sagar Mahadik[3], Ashwini Thokal[4]

[1,2,3]*UG Student, Department of Chemical Engineering, Bharati Vidyapeeth College of Engineering, Kharghar, Navi Mumbai, Maharashtra India*

[4]*Assistant Professor, Department of Chemical Engineering, Bharati Vidyapeeth College of Engineering, Kharghar, Navi Mumbai, Maharashtra India*

---***---

Abstract:- *Thermophotovoltaic (TPV) systems have slowly started gaining traction in the global sustainable energy generation realm. It was earlier believed to be a flawed method whose energy conversion efficiency was not high enough for commercial use. However, in recent times, research has picked up, addressing the need of increasing the energy conversion efficiency while making it economically viable for commercial applications. This paper will throw light on the various advancements in the field of TPV systems and investigate the potential avenues where TPVs may be used in the future. We will also be looking at the history of development of TPVs so that we may be aware of the humble beginnings of this game-changing technology which will be the shining light in our sustainable and clean energy future.*

Keywords: Thermophotovoltaics, sustainable, clean energy, history, future

1. INTRODUCTION

Thermophotovoltaics (TPVs) have long been earmarked as the way forward towards a sustainable and environment-friendly future. Fossil fuel depletion has started to show its effects on the global economy. Rising crude oil prices, coupled with worldwide climate change phenomena, have put mankind under tremendous pressure. Markets worldwide have become more volatile and sensitive, leading to destabilization of national economies. These global scenarios have urged mankind to go in search of renewable sources of energy. The problem with renewable sources of energy is that often they are not economically viable. This is the reason many innovative ideas and designs for harnessing natural sources of energy do not see the light of day. The current researchers contributing in the sustainable energy generation field have the most important responsibility of making breakthroughs in finding materials and methods such that renewable energy generation becomes practically feasible.

2. PRINCIPLE

To understand the working principle of TPVs, let us break down the term into three parts: Thermo (meaning Heat), Photo (meaning Light) and Voltaic (meaning Electricity produced by chemical action). Thus, a Thermophotovoltaic system uses light to heat up a thermal emitter, which in turn emits radiation (Infrared) on a photovoltaic (PV) diode to produce electricity. Conventional photovoltaics exploit only the visible band of solar rays for electricity generation. The visible band contains less than half the total radiation of solar energy. On the other hand, TPVs exploit the infrared radiation from hot bodies (thermal emitter) for generation of electricity. IR radiations contain more than half the total radiation of solar energy[1]. This makes TPVs a more lucrative option than conventional photovoltaic systems.

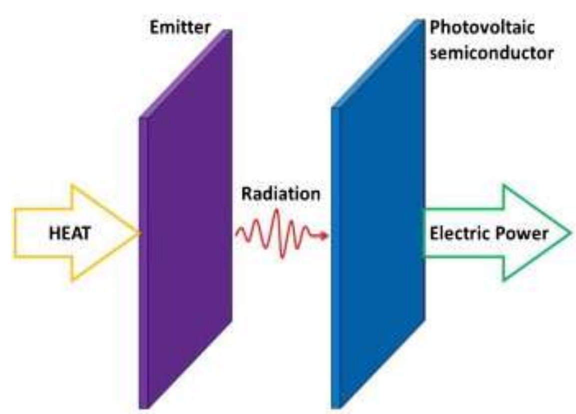

Figure 1: Basic schematic diagram of a TPV system [2]

A basic thermophotovoltaic system consists of two components: a thermal emitter and a photovoltaic diode cell. The thermal emitter absorbs the light from the sun (or any light source) and heats up. This causes the thermal emitter to emit IR radiation onto a PV cell. This is the basic mechanism of how a TPV system works.

TPVs have very little to no moving parts. This makes the TPVs highly reliable and ensures low maintenance costs.

TPVs can also respond to changes in demand. No other source of power can respond that quickly. TPVs are mostly useful in unmanned electricity generation grids.

3. HISTORY

To understand any technology, it is very essential to look at its roots; under what circumstances was it developed, how was it developed and who developed it. As far as TPV systems are concerned, it is unclear what led to its invention. We will be looking at the history of TPVs in two sections: the early phase and the solar energy phase[3].

3.1. The Early Phase

The first case is set in the year 1956 at MIT's Lincoln Laboratory (Lexington, MA). Dr. Henry H Kolm [4] constructed a TPV system using a Coleman camping lantern with an incandescent gas mantle as the emitter and using a silicon solar cell as the photoconverter and studied the output of the solar cell and carried out a total power output capability study the of the system and suggested some system improvements that translated into a potential conversion efficiency of 5–10%.

Professor Pierre Aigrain [5,6] is considered by many as the inventor of TPV. He conceptualized a direct energy conversion model during his stint as a visiting professor at MIT (Cambridge, MA) in late 1960 and early 1961.

During the 1960s, some of the professors at MIT started publishing technical research articles in conferences [7] and journals [8]. Professors Wedlock and Gray [9] concentrated on Ge cell development. Professor Schwartz, who was a graduate student at MIT at the time of Aigrain's lectures, joined the faculty at Purdue University (West Lafayette, IN) around 1963 and worked on developing Ge photoconverters [10] capable of operation under extreme conditions.

TPV systems are portable power sources with a low signature—especially low noise. This characteristic was exploited brilliantly by the US Army at Fort Monmouth. Since the early 1960s, Dr Emil Kittl and, later, Dr Guido Guazzoni played key roles in advancing this technology at Fort Monmouth. Dr Guazzoni first reported [11] high temperature emittance of some rare earth oxides that can act as competent TPV emitters.

It was a fact that not many industrial participants were interested in the development of TPVs. General Motors (GM) was one of the most active industrial participants in TPV development [12] early on. The concept of a photoconverter back surface reflector [13] for spectral control in a TPV system was developed during this program carried out by The Allison Division of General Motors, in collaboration with the Defense Research Laboratory.

In the mid-1970s, TPV development slowed significantly when the thermoelectric technology was preferred to satisfy the need for covert power sources because TPV development was not sufficiently advanced in comparison to the thermoelectric approach. General Motors also discontinued TPV development, but it was set back by various business challenges in the 1970 decade, along with many other automobile companies. The energy crises in the 1970s forced a redesign of the entire product line to optimize fuel economy requirements, along with emission regulations. This was the reason fossil fuel powered TPV systems did not develop further.

3.2. The Solar Energy Conversion Phase

The energy crisis in the 1970s helped in the development and acceptance of TPVs in a comparatively scale. The Electric Power Research Institute (EPRI) in US funded studies which studied whether coupling the output of solar-powered arrays into the utility grid is feasible. Among the topics investigated was the benefit of a TPV approach to shift the solar spectrum to longer wavelengths to match better available photoconverters. Swanson [14] at Stanford proposed such a system with a Si photoconverter. Horne [15] while at Boeing (Seattle, WA) patented a similar approach. At the same time, work was also going on at Boeing on conventional solar energy conversion applications. Fraas [16] and co-workers were developing tandem cells (GaAs/GaSb cell stacks) that exhibited a record 35% solar conversion efficiency.

Woolf [17] at GA Technologies (San Diego, CA) proposed InGaAs photoconverters for TPV applications. This work was not the introduction of a new class of narrow band gap cells but an attempt to improve on the performance of crystalline Si photoconverters. The Gillette Company based in Boston had developed selective fibrous rare earth oxide emitters [18] for TPV applications.

4. SOLAR THERMOPHOTOVOLTAICS

Solar TPVs are the way forward in response to the energy crisis the world faces today. This kind of TPV simply uses sunlight as a light source instead of fossil fuels, nuclear fuels etc., making it an eco-friendly option. Solar TPVs can act as a direct substitute to solar cells which are currently in use for electricity generation by using sunlight. The solar TPVs have a clear advantage over solar cells due to the fact that they have a high-density energy output as compared to solar cells[20]. This is due to the fact that solar TPVs use IR radiations which have high energy by virtue of their lower wavelength. Solar cells use visible light which has comparatively higher wavelength and hence lower energy.

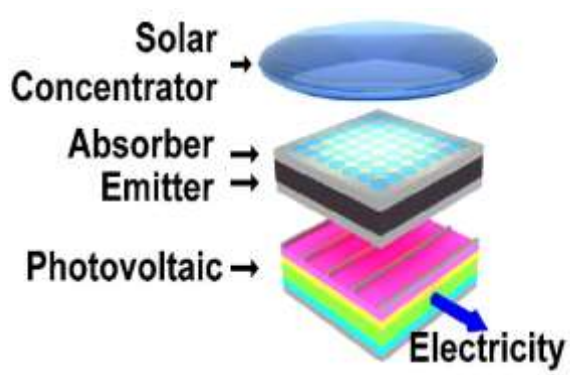

Figure 2: A solar TPV system [21]

As of today, the technology of TPV is continuously evolving. Solar TPVs are not yet commercially better than solar cells due to the fact that it has an extra element (thermal emitter) as compared to the solar cell. The thermal emitter is very costly and hence, increases the capital cost of TPVs. But, as discussed earlier, the higher density of output makes up for the initial expenditure and ultimately results in profits over a long period of time.

5. CHALLENGES

The emitter material is very important in terms of increasing the efficiency of a TPV system. The emitter material has to be heated at very high temperatures in order to emit IR radiations. Hence it is very critical to select emitter materials which can withstand high temperatures.

The PV cell converts the energy of photons into electricity. The photons, when incident on the PV cell, transfer their energy to the electrons. These electrons then absorb this energy and start moving. Movement of electrons produces electricity. Hence, it is very important to select PV semiconductor material such that the energy given by the photons is more than the bandgap of the semiconductor. This will ensure that the electrons get excited and the energy does not get wasted in any form.

The most important challenge faced by the TPVs is the solar conversion efficiency. The current efficiency is 3.2%, but the theoretical efficiency is 80%[22]. This shows how much development remains in this domain before it can become an economically viable option.

Given below is an experiment carried out to find out the efficiency of the TPV system[23].

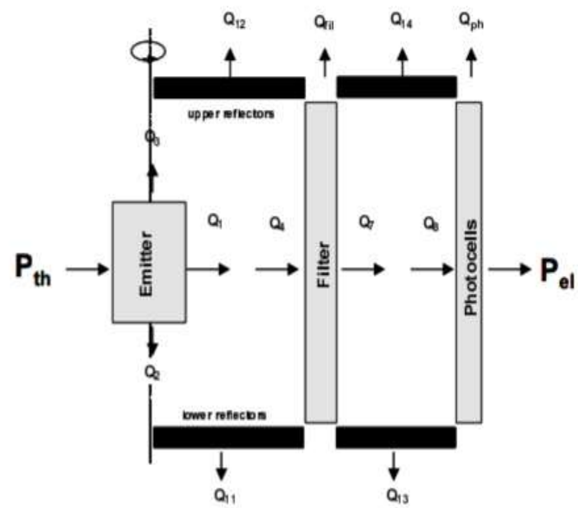

Figure 3: System Model[23]

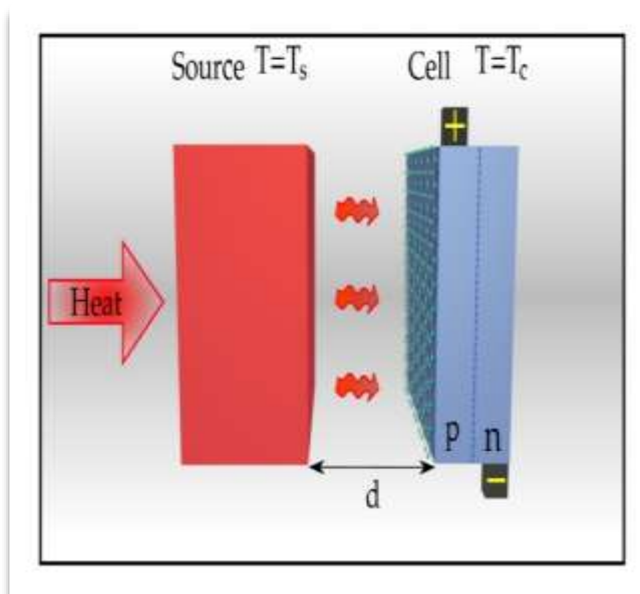

Figure 4: Near Field Thermophotovoltaics system[24]

	P_{th}[KW]	T_{em}[k]	P_{el}[W]	Efficiency[%]
sim	1.96	1777	47	**2.4**
exp	1.96		48	**2.4**

Table 1: Results of simulation

We can see that the efficiency of the TPV system was found out to be just 2.4%. This was an experiment carried out many years ago and since then, the efficiency has been increasing with each passing year.

6. NEAR FIELD THERMOPHOTOVOLTAICS[24]

Near field TPV is a method by option which can be helpful in achieving higher efficiency of TPVs. As the name suggests, the thermal emitter & the PV cell are in close vicinity. The distance between them is less than the wavelength of the radiation emitted from the thermal emitter. This ensures very little energy is lost while the photons travel towards the PV cell, and hence, increases the system efficiency.

Another way of increasing the efficiency of the TPV system is to minimize the losses incurred by the PV cell when the photons bounce back from the cell and get wasted. To counter this wastage, a graphene sheet can be used to ensure minimal losses.

7. CONCLUSION

TPVs have the potential to make large-scale renewable energy production possible. Even though the current efficiency is very low, the next decade will bring about a huge increase in TPV system efficiencies with newer technologies. With mass production, various materials useful in increasing the efficiency of the system will get cheaper. It is time the world starts to understand the importance of clean energy and adopt sustainable practices which will allow the future generations to experience a beautiful life.

REFERENCES

[1] Dricus, Thermophotovoltaics (STPV) just got a shot in the arm, 4th August 2016, Available: http://sinovoltaics.com/technology/will-solar-thermovoltaics-stpv-return/

[2] Micron-gap thermophotovoltaic systems enhanced by nanowires [Online]. Available: https://goo.gl/images/zKbhgF

[3] Robert E Nelson, "A brief history of thermophotovoltaic development", Semiconductor Science and Technology 18 (2003) S141–S143

[4] Kolm H H 1956 "Solar-battery power source Quarterly Progress Report", Solid State Research, Group 35 (Lexington, MA: MIT Lincoln Laboratory) p 13

[5] White D C, Wedlock B D and Blair J 1961 'Recent advance in thermal energy conversion Proc.', 15th Power Sources Conf. pp 125–32

[6] Broman L (1995), Thermophotovoltaics bibliography Prog. Photovolt., Res. Appl. **3** 65–74

[7] White D C and Schwartz R J (1967) "P-I-N structures for controlled spectrum photovoltaic converters", Proc. of NATO AGARD Conf. (Cannes, France, 16–20 March 1964) (London: Gordon and Breach) pp 897–922

[8] Wedlock B D (1963), "Thermo-photo-voltaic conversion Proc.", IEEE **51** 694–8

[9] Gray P E et al (1968), "Investigation of a PIN-structure germanium photovoltaic cell", Report DA-28-043-AMC-01978(E) (Cambridge, MA: MIT Press) p 80

[10] Schwartz R J (1971), "A theoretical and experimental investigation of planar pin thermophotovoltaic cells" Contract No. DAAB07-70-C-0129 (Lafayette, IN: Purdue University) p 145

[11] Guazzoni G (1972), "High temperature spectral emittance of oxides of erbium, samarium, neodymium, and ytterbium" Appl. Spectrosc. **26** 60–5

[12] Haushalter R W (1966), "Engineering investigation of a thermophotovoltaic energy converter Final Report", Contract No. DA-44-009-AMC-622(T) (Santa Barbara, CA: General Motors Defense Research Laboratories) p 185

[13] Werth J J (1963), "Thermo-photovoltaic converter with radiant energy reflective means", US Patent 3,331,707

[14] Swanson R M (1980), "Recent developments in thermophotovoltaic conversion", Proc. Int. Electron Devices Meeting (Washington DC 8–10 Dec. 1980) pp 186–9

[15] Horne W E (1977), "Conversion of solar to electrical energy", US Patent 4,313,024

[16] Fraas L M et al (1990), "Over 35% efficient GaAs/GaSb stacked concentrator cell assemblies for terrestrial

applications", Proc. 21st IEEE PV Specialists Conf. pp 190–5

[17] Woolf L D, Bass J C and Elsner N B (1986), "Theoretical and experimental investigation of variable band gap cells in thermophotovoltaic energy conversion", Proc. 32nd Int. Power Sources Symp. pp 101–9

[18] Nelson R E (1983), "Thermophotovoltaic technology", US Patent 4,584,426

[19] Chubb D L (1990), "Reappraisal of solid selective emitters", Proc. 21st IEEE PV Specialists Conf. pp 1326–33

[20] T.J.Coutts, "A review of progress in thermophotovoltaic generation of electricity", Renewable and Sustainable Energy Reviews 3(1999) 77-184

[21] Schematic diagram of a thermophotovoltaic system [Online]. Available: https://www.google.co.in/url?sa=i&rct=j&q=&esrc=s&source=images&cd=&cad=rja&uact=8&ved=2ahUKEwirtJf9s9DdAhWBdH0KHWqvCvMQjRx6BAgBEAU&url=http%3A%2F%2Fwww.mit.edu%2F~jeffchou%2Fresearch.html&psig=AOvVaw2gpGj7GCDhQ62R6sXUBZ4t&ust=1537767357072000

[22] Anand Upadhyay, Solar Thermophotovoltaics- Getting to 80% Efficiency, 6th October 2014 [Online]. Available: https://cleantechnica.com/2014/10/06/solar-thermophotovoltaics-getting-80-efficiency/

[23] B.Bitnar, et al., Simulation- and Demonstration model of a high efficiency thermophotovoltaic system[Online]. Available: http://lmn.web.psi.ch/shine/index.html

[24] Messina, R. & Ben-Abdallah, P, "Graphene-based photovoltaic cells for near-field thermal energy conversion", Sci. Rep. 3, 1383; DOI:10.1038/srep01383 (2013)