

Photonics from Al-Haitham to Optoelectronics of AMTEC

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ABSTRACT

The word “photonics” is derived from the Greek word “photos” meaning light. It covers all technical applications of light over the whole spectrum. Most applications, however, are in the range of the visible and near infrared light. With a brief history of classical work and tenets of optics, we will present electrical circuit of a thin-film device used in a fuel cell, called Alkali Metal Thermo Electric Converter (AMTEC). The device uses infrared radiation to knock out electrons from some alkali metal, which after going through a circuit and having done the prescribed work, meet the ions again. The system is closed and continues working as long as the radiation source is kept on. The longevity, power and efficiency of the device depend inversely to some extent on the thickness of electrodes used for collecting electrons freed from the alkali metal, as well as of the solid electrolyte. The details of the device’s circuit comprising both electrical and optical functions will be discussed.

Keywords: Infrared Radiation; AMTEC; Efficiency; Power Output

1. Introduction

The word photonics appeared around late 1960s. The term photonics developed as an outgrowth of the first practical semiconductor light emitters invented in the early 1960s and optical fibers, developed in the 1970s. However, it did not become a household word until the 1980s when Photonics Technology Letters was published at the end of the 1980s. A more fundamental question about light is, “What is light itself?” Though the Greek word photos, meaning the light, gave birth to the word “photon” and then “photonics” as a grandchild but did not explain correctly what is light. This has been the question for thousands of years in vogue. Ibn Al-Haitham, a thousand years ago in one of his books, “*Muqala fi Zau*” put the opening sentence “*What is light?*” He gave the theory, which is still in use as it was put then. Photonics research emerged as a discipline of its own from the kind of work that traditionally fell within the typical field of electronics. As an offshoot of electronics it was to describe a research area whose goal was to use light to perform functions, such as telecommunications, information processing etc. The term photonics emphasizes that photons have both particle and wave nature. Or in other words they are neither particles nor waves. In general it covers all technical applications of “light” over its entire spectrum in its wide sense ranging from gamma rays to radio waves. The discipline of photonics includes

the generation, emission, transmission, modulation, signal processing, switching, amplification, detection or sensing of light. Optics, of course, preceded the discovery that light is quantized. Optics tools include the refracting lens, the reflecting mirror, and various optical components known prior to 1900. Key tenets of classical optics, such as Sahl-Hatham-Snell law [1], Newton’s corpuscular hypothesis for light propagation, wave propagation of light based on Huygen’s principle, Maxwell’s equation, wave equations, all of them do not depend on quantum properties of light. Photonics is closely related to optics. Most of the applications, however, are in the range of the visible and near infrared light. It is the infrared and near infrared region of electromagnetic radiation or in simple language thermal range, which are used in the working of Alkali Metal Thermal Electric Converter (AMTEC) cell to be discussed here.

Photonics, in the context of modern optics, is more related dealing with quantum optics, quantum electronics, electro-optics, optomechanics, and optoelectronics. However, each area has slightly different connotations among the scientific communities and in the marketplace. Quantum optics often connotes fundamental research, whereas the term photonics is used to connote applied research and development. More specifically it connotes the particle properties of light, the potential of creating signal processing device technologies using photons, the appli-

cation of optics more in practical aspect, and an analogy to electronics.

The term quantum electronics was used for the area of physics dealing with the effects of quantum mechanics on the behavior of electrons in matter, and their interactions with photons. It is today rarely considered a sub-field in its own right, as it has been absorbed by other fields. The term was mainly used between the 1950s and the 1970s. Today, the research output of this field is mainly used in quantum optics, especially for the part of it that draws not from atomic physics but from solid-state physics.

Electro-optics, not to be confused with optoelectronics, involves components, devices and systems which operate by modification of the optical properties of a material by an electric field. This branch of technology deals with the interaction between the electromagnetic and the electrical or in modern terminology electronic and optical states of material.

Optomechanics can be referred to as the study of the interaction of photons (electromagnetic radiation) with mechanical systems via radiation pressure, and also the manufacture and maintenance of optical devices and parts, such as fiber aligners, mirror mounts, optical mounts, translation stages, rotary and kinematic stages, pedestals and posts, rails, micrometers, screws and screw sets. It may also include optomechanical design and integration with exterior package, manufacture and maintenance of fiber optic materials, and design and packaging of rugged optical trains in compact form.

The term optoelectronics connotes devices or circuits comprise both electrical and optical functions, *i.e.*, a thin-film semiconductor device. The term electro-optics came into earlier use and specifically encompasses nonlinear electrical-optical interactions applied, *e.g.*, as bulk crystal modulators. It also includes advanced imaging sensors used typically for surveillance. It is the design, manufacture and working of AMTEC as a whole, which pertains to the device domain of optoelectronics.

AMTEC is an infrared regenerative electrochemical device for the direct conversion of heat into electricity. While AMTEC technology development is primarily focused for deep space missions because of its longevity and high efficiency under static conversion, it is also expected to have many terrestrial uses. Its simulated design has shown its longevity as much as fifteen years. Some of its laboratory devices have achieved efficiencies as high as 19%. Small system designs using AMTEC have shown 27% cell and 23% system efficiencies. An Optimized AMTEC can, however, potentially provide a theoretical efficiency close to Carnot efficiency almost up to 40% [2]. It has no moving part thus creating no noise with the potential for low maintenance, high durability and reliability. As it has no moving parts it is not

subjected to any material wear and tear. There is no vibration or uncompensated momentum present in AMTEC, which reduces the chances of corrosion. It has the ability to use infrared energy as an input from high temperature combustion, nuclear, radioisotope, solar or heat rejected from other devices [3-6]. A number of research programs on AMTEC have been focusing on improving its performance characteristics and technology improvement. Of course, these efforts have successfully resolved many of the important technological issues pertaining to its design and fabrication. The performance level, however, achieved until today is still below the expected potential of AMTEC. During an extended testing of an AMTEC model the maximum power of its output was observed (**Figure 1**) to be decreasing from 2.49 W to 1.27 W over a period of 18,000 hours of operation [7]. The degradation is primarily due to its solid electrolyte, called bête alumina solid electrolyte (BASE). The role of electrodes is insignificantly small compared to BASE [8].

Before we discuss their respective contributions to the power out and efficiency it may be in order to give a brief description and working principle of AMTEC. This is mostly borrowed from an encyclopedic article of the author [9].

2. Physical Description of AMTEC

Initially AMTEC was developed as liquid-anode cycle but soon the vapor-anode cycle system took over. The use of the vapor-fed AMTEC cycle system has presently been in the vogue and being investigated. A typical AMTEC unit is sealed, housed in a sealed container. The working fluid should be so selected that it should have a high negative potential, lightweight and abundantly available for cost effectiveness. An alkali metal with relatively low melting point would satisfy these qualities. Out of number of possible samples sodium (Na) is chosen for this task. At the heart of AMTEC lies a solid electrolyte made of a dense micro-crystalline sintered ceramic material beta" aluminum solid electrolyte (BASE) ($\text{Na}_{5/3}\text{Li}_{1/3}\text{Al}_{32/3}\text{O}_{17}$) in the form of individual tubes connected in series as shown in **Figure 2**.

The BASE separates two regions of alkali (sodium in this case) vapor introduced; a high-temperature (900 K – 1300 K) high-pressure (20 - 100 kPa) region and a low-temperature (400 - 700 K), low-pressure (<100 Pa) region, see **Figure 2**. From the physical dimensions of this type of AMTEC cell it looks about a D-size dry cell. Two thin, porous electrodes are placed on inside and outside walls of the BASE, as shown schematically in **Figure 3**.

The electrode mounted on the inner side of the BASE acts as anode and the one on the outer side of the BASE is treated as cathode. The inner and outer electrodes are

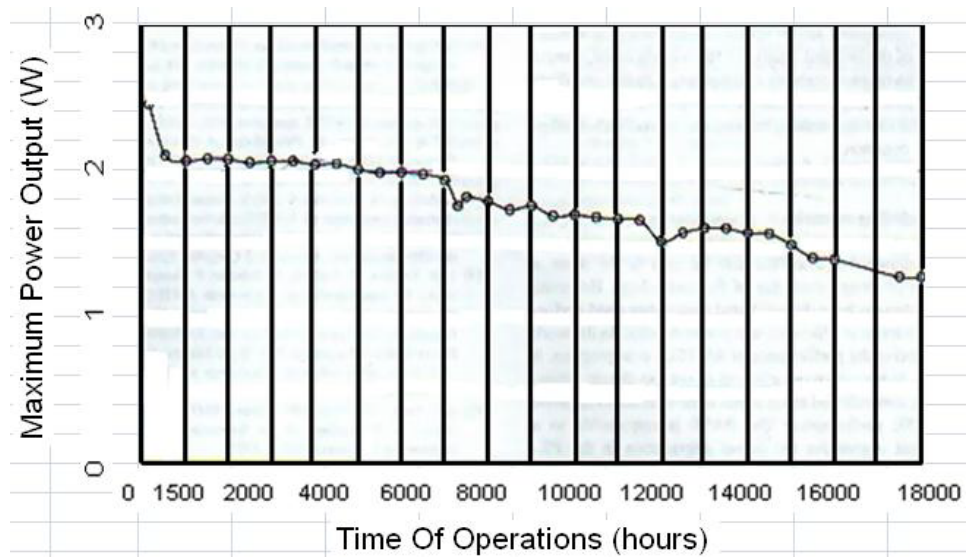


Figure 1. Power output of AMTEC as a function of time of operation.

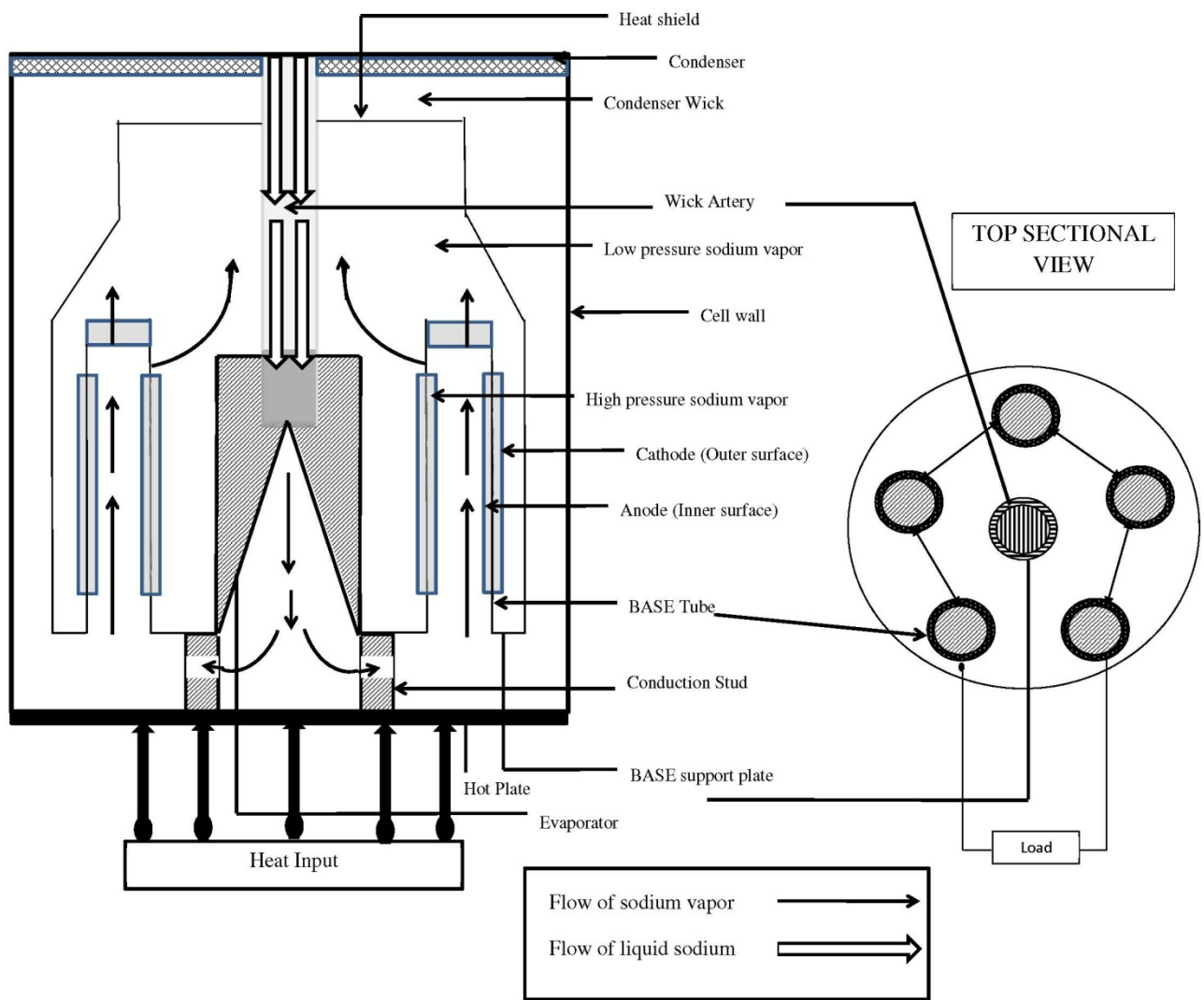


Figure 2. Schematic diagram of AMTEC with 5 BASE tubes.

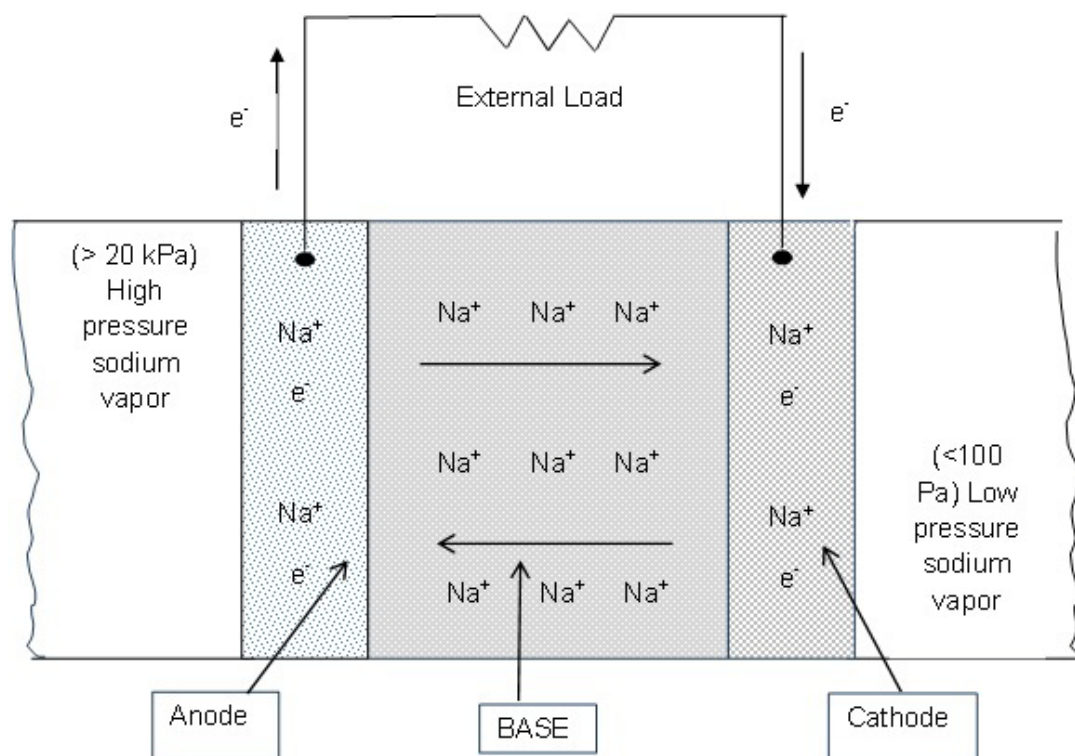


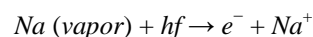
Figure 3. Relative positions of BASE, anode and cathode of AMTEC.

each connected with current collectors. One of the collectors collects electrons at the anode (high pressure side of BASE) and conducts them through an external load. Electrons from the external load are brought back to the cell at the cathode (low pressure side of the BASE) for the recombination with sodium ions. The requisite leads connecting the two electrodes carry the electric current through the load. The working fluid, initially in the liquid state stored in the condenser at one of the ends of the cell, is carried by a capillary tube, called sodium return artery into the evaporator placed at the other end of the cell, where it is heated and turned into vapor, see in **Figure 2**. The evaporator thus maintains liquid-vapor interface during the operation of the cell. The evaporator side end carries a hot plate, which is heated from the external infrared source. The far end of the cell, where the condenser is housed releases the heat of sodium condensation. The cell contains a radiation shield, laid against the cell walls above the BASE tubes to reduce the parasitic energy losses through the cell walls. In addition to radiation shield a chevron radiation shield system consisting of a requisite number of chevrons at desired angles is placed above the BASE tubes when needed for maximizing the power output and efficiency. The cell is operated in the vacuum.

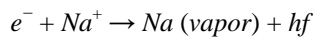
3. Working Principle of AMTEC

On applying the infrared radiation or/and any source of

heat at one end of the cell, where the inner container is mounted, produces the electric current at the other end of the cell. The sodium vapor pressure at the anode/BASE interface (the high-pressure side) is equal to the saturation pressure at the evaporator (where liquid sodium is converted into vapor) temperature. The pressure differential between the two sides of the BASE is associated with potential energy, which can be converted to useful work through sodium. As the liquid sodium at condenser temperature enters the evaporator in the hot region of the cell, it starts absorbing the externally supplied heat until it vaporizes and reaches the desired temperature of the inside BASE tube. The inside BASE tube temperature is kept slightly higher than that of the evaporator to prevent condensation of sodium in the anode cavity and the potential electric shorting of the cell. As a result of the high pressure, sodium vapor tries to expand. The β' -alumina is impermeable to neutral atoms and negative charges. Thus, the only way for the pressure to be released, in other words, for the vapor to expand, is for neutral sodium atoms to ionize allowing the sodium ions to pass through the BASE wall. The sodium atoms, hence, ionize producing sodium ions and free electrons. Due to the thermodynamic pressure across the BASE ionization of sodium metal vapor occurs in the hot region at the interface of anode and the BASE with the following electrochemical reaction:



Here h is plank constant and f is the frequency of infrared radiation. The BASE permits the sodium ions to pass through its material and the pressure differential causes the movement of the ions. The positive sodium ions accumulate on the low-pressure side. The electrons collect on the current collector at the high-pressure side resulting in an electrical potential, which balances the pressure differential and prevents further flow of sodium ions. With appropriate electrodes, this electrical potential can be utilized to drive an electrical current when a load is placed on the system (*i.e.* connecting the inner and outer electrodes with a light bulb, CD player, or deep space probe for example). The electrons flow from the anode through the lead and the external load, to the cathode on the outer (low pressure) side of the BASE. Sodium ions that have passed through the BASE reach the interface between the BASE and the cathode where they recombine with the electrons to form neutral sodium atoms again as they were to begin with. At the interface of the cathode and the BASE the following reaction takes place:



The neutral sodium atoms escape from the interface of the BASE and the cathode in the form of sodium vapor at low pressure in the outer low-temperature low-pressure region. The low-pressure sodium vapor goes to the condenser where it releases its energy in condensation and condenses to the liquid state. Nearly entire temperature drop occurs in the low-pressure vapor state. After condensation the condensed liquid sodium goes to the wick annulus to the inlet of a dc electromagnetic pump or a porous capillary wick. This system is used to return the liquid sodium to the evaporator in the high-pressure region where it is converted to high-pressure vapor. This way the sodium continues to recycle and maintains the cell operation. A typical cell contains approximately 3 grams of sodium circulating through the loop at a rate up to 0.3 grams per minute.

The overall working of AMTEC is based on four prin-

ciples dealing with 1) thermal, 2) vapor pressure loss, 3) electrochemical and 4) electrical models. These principles or models and their functions could not be described in detail in the space provided here. That description involves lot of mathematical derivations and expressions. It should be borne in mind that the aforementioned principles do not work independently of each other. Instead, they are closely coupled to each other. A method is therefore, developed to ensure a good coupling to each other, thus allowing minimum losses over all and providing a good efficiency of the cell. It has been well known that the AMTEC performance mainly depends on BASE and to some extent on electrodes [8]. One of the parameters affecting the AMTEC efficiency is the thickness of BASE and electrodes. With the nanoscale modern technology available [10,11] we have examined the influence of the variation in thickness of BASE and electrodes.

4. Results of AMTEC Improvement with Nano Scale of Electrodes and BASE

We have studied the optimization of power and efficiency of AMTEC by varying the thickness of its electrodes and BASE. The original dimension of thickness of electrodes and BASE on which the analysis has been performed are respectively 5.0×10^{-7} m and 5.08×10^{-3} m. The optimum thickness of the electrode has been found to be 1.115×10^{-7} m with the improvement in efficiency of 1.06%. This is not much of the improvement of course. However, when the thickness of the BASE was optimized and reduced to 1×10^{-4} m the efficiency improvement has been obtained by 28%, see **Table 1**. The optimization of power output for the same set of thickness parameters was then performed, similar results were obtained. With the electrode optimization only the improvement was 0.6% but with the optimization of the thickness of the BASE the improvement in the power was found to be 14.8% see **Table 2**.

Table 1. Efficiency optimization for electrode and BASE thickness at various temperatures.

Thickness of BASE Tube	Thickness of Electrode	1023 K	% Change	1123 K	% Change	1173 K	% Change
0.508D-3	5.0D-6	5.898855		8.116319		9.115548	
0.508D-3	1.115D-7	5.951673	0.90	8.199821	1.029	9.212263	1.061
1.0D-4	1.115D-7	7.324257	23.27	10.35095	26.504	11.76178	27.969

Table 2. Power optimization for electrode and BASE thickness at various temperatures.

Thickness of BASE Tube	Thickness of Electrode	1023 K	% Change	1123 K	% Change	1173 K	% Change
0.508D-3	5.0D-6	1.386651		2.583163		3.300124	
0.508D-3	1.115D-7	1.403511	0.286%	2.620202	0.456%	3.350441	0.552%
1.0D-4	1.115D-7	1.841393	7.423%	3.598503	12.054%	4.697319	14.776%

5. Summary and Concluding Remarks

A brief history of photonics and optoelectronics with their implication has been presented. The role of infrared part of electromagnetic radiation has been studied with respect to power generation by AMTEC. The optimum efficiency of the device has been analyzed with an improvement of 28% if the thickness of the BASE is reduced by half a millimeter and that of the electrodes is reduced to 111.5 nm from 500.0 nm. With the same set of thickness parameters of electrodes and the BASE the improvement in power was found to be 14.8%. The efficiency and power production are temperature dependent, see **Tables 1** and **2**. These values were obtained by operating AMTEC at a temperature of 1173 K. The change in electrode thickness improves the performance somewhat insignificantly. The variation in the BASE thickness, however, makes the improvement significantly high. This supports the previously established role of the BASE with respect to the AMTEC performance that its degradation or improvement depends primarily on the BASE.

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