THERMIONIC CONVERSION AS THE NEXT STEP IN THE MOVE TO RENEWABLE ENERGY

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ABSTRACT: As the world grapples with the consequences of climate change, our energy needs continue to grow and evolve. While the emission of electrons from the surface of a heated material has been a well-understood physical process for over seventy years, obstacles such as material work function and space charge prevented the development of sufficiently efficient converters. Despite these setbacks, theoretical efficiencies and other benefits, such as long operational lifespan and a lack of moving parts, have continued to drive technology interest. With recent advancements in material fabrication and device manufacturing, the thermionic converter is entering a new era. The development of semiconductors, nanotechnology, and combined emission mechanics makes necessary work functions achievable. Simultaneously, introducing interelectrode plasmas, microscale manufacturing, and interstitial gate electrodes is combating space charge. This paper provides a background on the physics of the phenomenon and summarizes the breakthroughs recently achieved in converter design and efficiency. We gradually shape a narrative that offers insight into potential applications and examines how these devices can contribute significantly to our push towards renewable energy and why their research and development must continue.

Introduction

As global energy demands increase, energy output requires high electron density, narrow electron-energy distributions, short emission times, and efficient excitation. In practice, these are all requirements that thermionic converters, which convert heat directly into usable energy, have struggled to realize (Trucchi, 2017). Nevertheless, thermionic energy converters offer us the most well-rounded approach to maximizing energy output as we reduce dependency on fossil fuels. Recent developments in material fabrication, semiconductors, nanotechnology, and a deeper understanding of their underlying physical process have breathed fresh life into the thermionic community (Go, 2017; Hogan, 2019). While there is much work to be done, thermionic energy converters (TECs) are rounding a corner, positioning them as key players across various industries.

This paper aims to provide a broad but succinct overview of the history of and process behind thermionics. As a means to advocate for the continued development and application of thermionic converters, the paper begins by identifying obstacles that have prevented their widespread adoption, then moves to recent advancements and breakthroughs in the technology, and ends with possible future applications.

History

It has not been uncommon for discoveries to be dismissed throughout history when their practical application comes into question. A British Parliament Committee suggested Edison's light bulb was "unworthy of the attention of practical or scientific men (Nguyen, 2016)." Einstein himself believed we would never directly detect gravitational waves due to their subatomic scales (Gravitational Waves Detected 100 Years *After Einstein's Prediction*, 2016).

Thermionic emission as a practical energy provider was no exception. Conceptually, the technology is not short of appealing characteristics. Theoretical efficiencies trend upwards of 82% while the absence of moving parts prevents friction, keeps entropy low, and allows for long operational lifespans (Trucchi, 2017). Also, it generates no carbon emissions whatsoever.

While a handful of scientists observed it decades before the process was thoroughly understood, the theory of thermionic emission as we know it today began to develop over one hundred years ago. While studying the conductivity of gases in 1853, Henri Becquerel measured the current between hot and cold platinum wires. Though he failed to recognize the significance of thermal energy at the cathode, this was one of our first examples that something larger was at play (McCarthy, 2014). Twenty years later, Frederick Gutherie discovered that a negatively-charged iron sphere would lose charge if it were heated to extreme temperatures and placed in a vacuum, while a positively charged sphere would not (McCarthy, 2014; Mitchell, 2003). In 1883, Thomas Edison observed the potential of the process while attempting to improve his incandescent lamp. When he inserted a thin wire above the heated filament, he discovered a current flowing between the two metals (Gallet, 2001; Lienhard). Finally, with J.J. Thomson's work in 1897, the electron was recognized as a distinct particle, and the theory of thermionic emission was established (A Look Inside the Atom, 2007).

While this summarizes some of the initial discoveries that prompted a more thorough academic understanding of the phenomenon, it was not until the 1950s, fueled by competition with the Soviets during the Cold War, that American understanding translated into application. It is no coincidence that this technology's aggressive expansion coincides with both countries' nuclear and space-based ambitions (Go, 2017). A thermionic converter's real strength lies in producing energy from waste heat as a cogenerator. Moreover, its lack of moving parts and compact size made it an attractive option for space-based missions (Morris, 1980; Trucchi, 2017). Sadly, despite significant contributions, challenges in material composition, device design, and overall public distrust of nuclear energy, led the United States to shift towards fossil fuel consumption in the 1970s. Our absence yielded credit for many advancements in materials and converter design to the U.S.S.R. (Go, 2017).

Thermionic Emission

Thermionic emission is one of three primary methods of electron emission. All forms of emission refer to the ejection of electrons from a material. What distinguishes each type is the source of energy for the electrons. As the name suggests, thermionic emission involves thermal energy (McCarthy, 2014). When a material is heated sufficiently, the energy absorbed by its electrons allows them to escape, becoming unbounded (Abdul Khlaid, 2016). A common metaphor to help visualize the process is the boiling off of electrons from the material's surface (Go, 2017). Different materials require different amounts of energy because of variances in atomic structure, purity, and surface morphology (Go, 2017; Abdul Khalid, 2016). The minimum amount of energy required to displace one electron from a material's surface to a point just beyond the surface is called the work function (Schlaf). The work function of most materials is on the scale of several electron volts (*Thermionic Energy Conversion*; Trucchi, 2017).

As Edison observed, this emission phenomenon, which he humbly dubbed "The Edison Effect," can produce a current between two electrodes capable of performing work (Foundation, 2013; Lienhard). The cathode, or emitter, is the heated material that emits electrons. The anode, or collector, is the material that collects the emitted electrons (Go, 2017). In its most elementary design, a thermionic converter has three components: the electrodes, connecting circuitry, and an electric load, such as a resistor (Abdul Khalid, 2016).

As electrons accumulate on the collector, a negative charge induces a voltage difference between the electrodes. Introducing a resistor then drives a current through the circuit (Abdul Khalid, 2016). This simplicity affords TECs low entropy; with no moving parts to create friction, they experience longer operational lifespans and run silently (Go, 2017), contributing to their ability to help optimize existing energy production.

Traditional Device Design

As mentioned previously, meaningful progress in thermionics as an honest energy supplier did not arrive until the 1950s. It was then that George Hatsopoulos, from the Massachusetts Institute of Technology, developed two prominent converter designs. He designed each method to facilitate electron transport across space between electrodes called the interelectrode gap (Abdul Khaid, 2016). The first design was the vacuum TEC, or VTEC. It included a vacuum space between the electrodes to minimize atomic obstacles, allowing electrons to apply all their kinetic energy to crossing the gap instead of depleting it on costly elastic collisions (Bickerton, 2017; Abdul Khalid, 2016). The second design was called the vapor TEC, and involved filling the gap with a positively charged, ionized alkaline metal vapor, usually cesium, due to its low ionization energy (~3.9 eV) (Go, 2017). The single electrons in their outer shells make alkaline metals prime candidates for these applications (McCarthy, 2014). This positively charged vapor would help to “pull” electrons from the emitter, lowering its work function, though inherent downsides covered later abate this gain.

Typical working conditions expose emitters to extreme and repetitive heating and cooling cycles. Refractory metals are, therefore, frequently the material of choice (Foundation, 2013; Go, 2017; Katoh, 1997). While their definition remains relatively loose, all refractory metals exhibit hardness at room temperature and are resistant to extreme heat, with most melting points occurring above 2,000 degrees Celsius. Five metals seem to make every list: Tungsten, Molybdenum, Niobium, Tantalum, and Rhenium (Rowe, 2003). That heat resistance also makes them renitent to creep, a mechanics of materials term referring to the long-term strain a material is subjected to by external forces (Foundation, 2013). These forces gradually compromise a material’s structural integrity until it ultimately fails. This additional trait prolongs operational lifespan and is another reason their use is appropriate in emitter design, providing a cost-efficient benefit in commercial, consumer, and government applications.

Theory

The current density in thermionic conversion is governed by the Richardson-Dushman equation, although a more comprehensive understanding of the parameters involved is required.

$$J_{Thermionic} = AT^2 e^{\frac{-\phi}{k_B T}} \text{ (eq. 1)}$$

where T is the absolute temperature of the cathode, phi is the work function of the emitter material, k is Boltzman’s constant, and A is the effective Richardson constant, a parameter of the material (Go, 2017; McCarthy, 2014). The effective Richardson constant is itself further defined as,

$$A = \lambda A_0 \text{ (eq. 2)}$$

where lambda is a corrective parameter (1) that considers the material surface’s reflection coefficient and A_0 is a universal constant (Crowell, 1965). A_0 is defined as,

$$A_0 = \frac{4\pi m k^2 e}{h^3} = 120 \ \frac{A}{cm^2 K^2} \text{ (eq. 3)}$$

where m is the electronic mass, e is the electronic charge, and *h* is Planck's constant (van Dommelen, 2002).

We can immediately notice, to maximize current density, one must simultaneously strive for the lowest possible work function and highest possible temperature. While conceptually, this may appear straightforward, it is deceptively challenging. Among the several considerable hurdles plaguing the efficiency of TECs, one of the largest is the fact that several variables are essentially at odds with each other. For example, specific material may be optimal for an emitter because of its low thermal conductivity since we try to avoid heat loss. A material with high thermal conductivity may then be preferred for the collector to dissipate the heat collected via thermalization with electrons. However, both electrodes require high electrical conductivity, which could conflict with the emitter's thermal needs since the two conductivities are typically connected intrinsically (Go, 2017).

Obstacles

To appreciate the competing nature of the variables involved, we will provide a more definitive explanation of each. In this section, we identify and discuss the various obstacles that have historically inhibited thermionic conversion efficiency.

Work Function

A material's work function is often described as the energy gap between its Fermi level and the vacuum level (preventing an electron from being dislodged from its surface) or the minimum energy required to displace an electron from the surface of the material to a point just beyond the surface (Schlaf). However, this can vary slightly with semiconductors, which, in modern approaches, are frequently used. The work function is essentially a measure of how tightly a material clings to its electrons; the lower the work function, the less energy required (Chao, 2016). It is a complicated parameter to determine precisely. In addition to being affected by the material's overall atomic structure, many external and internal factors contribute, such as purity of the material, bulk structure, surface morphology, and even thermal expansion (Kahn, 2016; Go, 2017; He, 2008).

As shown in the semiconductor energy diagram in figure 1, electron energy in an atom is quantized. The valence band maximum represents the highest occupied molecular orbital (HOMO), which is the highest energy obtained by an electron at zero degrees Kelvin. The conduction band minimum represents the lowest unoccupied molecular orbital (LUMO). The gap between the two bands is the additional energy an electron must obtain to move from the valence band to the conduction band. The electron must lose this amount of energy to move in the opposite direction. The Fermi level is the energy of the highest occupied orbital shell when measured at zero degrees Kelvin. It has been intentionally designed to reside within the energy gap to prohibit electron promotion into the conduction band, where it is free to

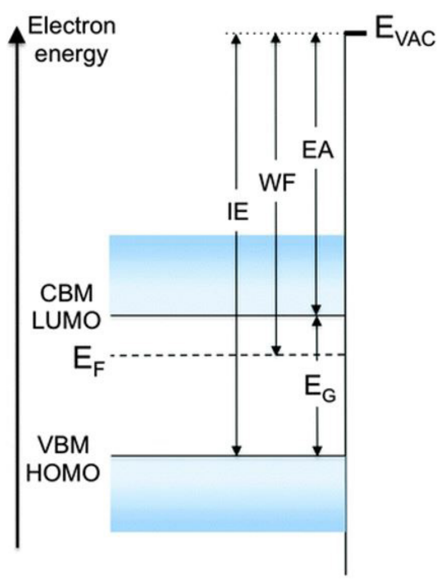


Figure 1: Energy diagram for the electrons of a semiconductor where EFis the Fermi level, EGis the energy gap between valence and conduction bands, EA is the electron affinity of the material, WFis its work function, and IEis ionization energy (Kahn, 2016).

travel throughout the material unless it obtains sufficient energy (Kahn, 2016). This energy difference is called the Fermi energy. Since the conduction band energy level is still well below the vacuum potential's energy level, the work function is then the difference between the vacuum potential energy and the Fermi level (Schlaf). Once an electron has received this energy, it is ejected from the surface into the vacuum space between electrodes (Go, 2017).

Given that work function is a material property, it makes sense that a TEC emitter and collector could have differing work functions, which is preferably the case. The maximum voltage a TEC can produce is this difference, as described by

$$eV_{out} = (\varphi_e - \varphi_c) \text{ (eq. 4)}$$

while the overall power density is given by

$$P = JV_{out} = J\left(\frac{\varphi_c - \varphi_c}{e}\right) \text{ (eq. 5)}$$

Herein lies the first considerable complication (Go, 2017; Swifter, 2018). If eq. 1 requires the pursuit of the lowest possible value for an emitter's work function, then eq. 4 requires a work function even lower for the collector to maximize output voltage. Ideally, the collector's work function should be ~0.5 eV, and practical application requires a difference of at least 1 eV (Go, 2017; Abdul Khalid, 2016). This condition presents a substantial challenge for materials.

Space Charge

As electrons in the emitter are adequately excited, they use most of their kinetic energy to overcome the vacuum potential. This may or may not leave enough energy for them to cross the interelectrode gap (Schlaf; Khan,

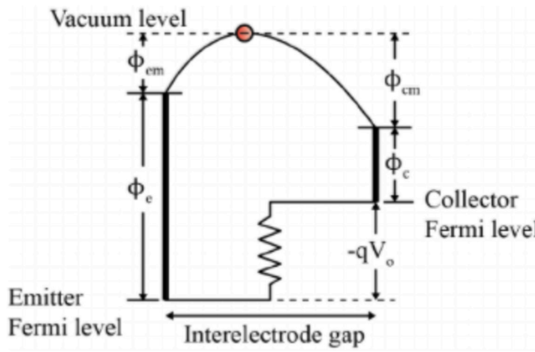


Figure 2: An energy diagram for a TEC showing the different Fermi levels between emitter and collector and comparing their different work function needs. The work functions denoted by em and cm refer to the repulsive force of the space charge phenomenon. It illustrates the additional energy required for the surface to emit a particle when space charge is present (Abdul Khalid, 2016).

2016). This scenario can produce a cloud of electrons between the electrodes if the current density is high enough (Go, 2017). The negative charge of this cloud is capable of repelling new electrons attempting to cross the gap and, if it becomes strong enough, can prevent emission altogether (Swifter, 2018; Go, 2017; Trucchi, 2017). This effect is known as space charge, and it may be the single most considerable challenge in usable TECs as it can obliterate current between the cathode and anode (Go, 2017). As shown in figure 2, TEC energy diagrams often account for it with its own symbolic work function. Accounting for the resulting diminishing current requires consideration of the Child-Langmuir Law (Go, 2017).

$$J = J_{CL}\left({}_2F_1\left(\tfrac{1}{4}, \tfrac{3}{4}, \tfrac{7}{4}, -\tfrac{eV_0}{2mc^2}\right)\right)^2 \text{ (eq. 6)}$$

where ${}_2F_1$is the hypergeometric function, e is the electron charge, V_0 is the electrostatic potential, m is the electron mass, c is the speed of light, and

$$J_{CL} = \frac{4\varepsilon_0}{9D^2}\sqrt{\frac{2e}{m}}{V_0}^{3/2} \text{ (eq. 7)}$$

where ε_0 is the permittivity constant of free space, and D is the distance between the electrodes (Gonzalez, 2017).

Advances

Nevertheless, as stated previously, there are reasons to remain optimistic. Modern approaches have provided a plethora of breakthroughs capable of addressing these obstacles and advancing thermionic technology.

Materials Fabrication

Much of the progress in thermionic design comes from emerging techniques in materials fabrication and blending of emission and absorption processes. These developments seek to address the obstacles mentioned above regarding material work function (Go, 2017).

Semiconductors are materials with conductivity between an insulator and a conductor and are vital to design more efficient TECs. The most effective way to describe the distinction between these three material types is through energy diagrams, like the one visible in figure 3 (What are Semiconductors).

Energy diagrams depict the various orbital shells of atoms making up a material as horizontal bands. The highest energy level obtained by an electron when the atom is at zero degrees Kelvin marks the material's Fermi level (Maestra, 2020). The band in which that electron resides is the valence band, the outermost occupied shell of the atom. There are energy bands above the valence band called conduction bands. These bands overlap just slightly in metal, as seen in figure 3c, with the Fermi level residing in the overlap (R. Nave). While no conduction occurs at absolute zero, this trait illustrates the minimal energy input required to run current through a conductor. Any electron that resides within the conduction band can flow with the current, and the overlap of the two bands ensures that a conductor lives up to its name.

However, if small amounts of a second element are added, such as phosphorus, which has five valence electrons, it would still share

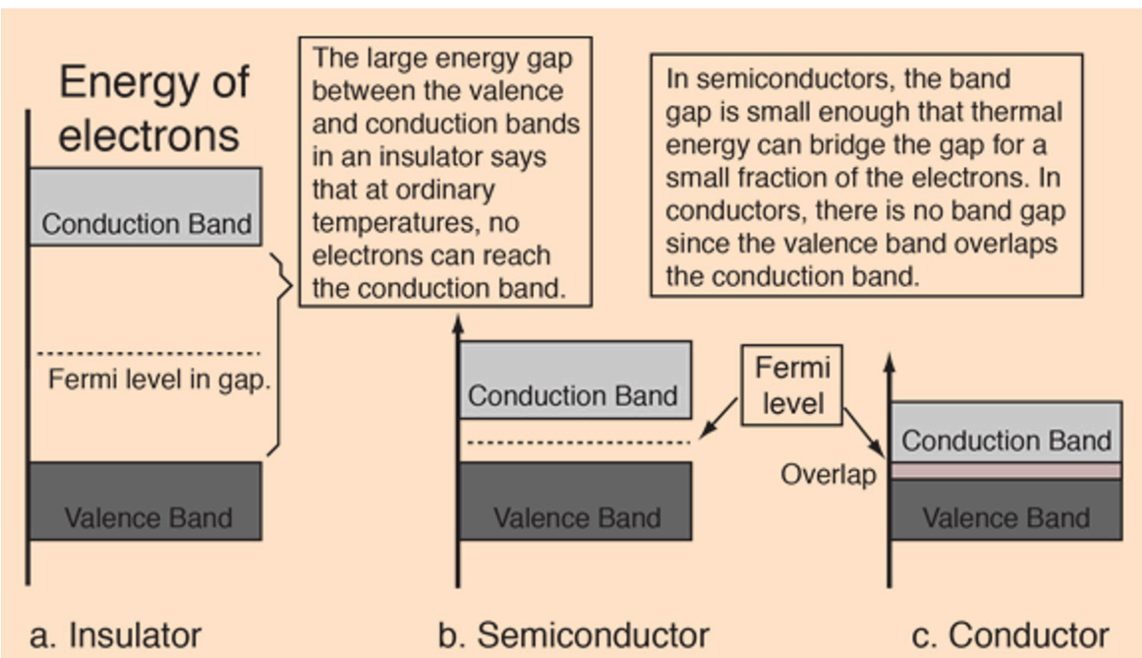
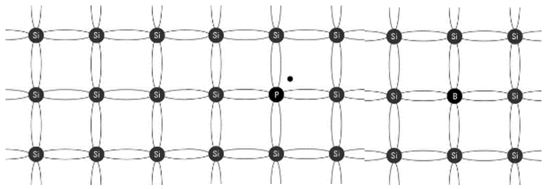


Figure 3: (a) shows the energy diagram of an insulator, characterized by a large energy gap between valence and conduction bands; (b) shows the energy diagram of a semiconductor with a moderate energy gap; (c) shows the energy diagram of a conductor with the valence and conduction bands overlapping (R. Nave)



(a) (b) (c)

Figure 4: (a) shows a lattice of pure silicon; (b) shows silicon doped with phosphorus; (c) shows silicon doped with boron (Lowe)

two electrons and receive six. However, now it has an extra electron with no place to live (fig. 4b). This condition describes an n-type semiconductor and is possible because of doping, which involves adding impurities to a material. In this scenario, phosphorus is the dopant. In figure 4c, we see a silicon crystalline structure doped with Boron. Boron only has three electrons in its outermost shell. This results in an empty space in its valence shell. As an electron moves from one atom to fill it, it leaves behind a hole that also requires filling. In the presence of a potential, a definitive direction can be encouraged for this “fill a hole, leave a hole” pattern and current can be induced. This process describes what is known as a p-type semiconductor (Lowe).

Even minimally, doping a material has a strong influence on its Fermi level and, therefore, its conductivity (Go, 2017). Pairing semiconductors with doping is one of the most promising advancements in emitter design because it flaunts the possibility of retaining a material’s resistance to thermal conductivity while increasing its electrical conductivity. As the technique continues to advance, it may be possible to design a material exactly to whatever work function requirements are needed (Swifter, 2018). A recent study reported a work function of 1.7 eV for a semiconductor composed of barium oxide deposited on polycrystalline-silicon carbide substrate with a thin layer of tungsten for adhesion purposes. While further development is still required, it remained stable for several hours at temperatures between 900 and 1400 degrees Kelvin. Another study reported a work function of 0.9 eV from phosphorus-doped polycrystalline diamond films on metallic substrates (Abdul Khaid, 2016).

As stated earlier, thermionic emission is just one of the three primary methods of electron emission. Secondary emission is another process, most frequently used in combination with photoemission. Although this is not a primary emission mechanism, it is possible to create a chain reaction through electron-multiplying stages. By accelerating emitted electrons towards a series of cascading dynodes, which emit several low-energy electrons for every high-energy electron that strikes them, it is possible to significantly increase electrons’ absolute yield value, increasing the current produced (Keidar, 2018). The chief drawback to this method is that since the photocathode’s sensitivity depends on the photon’s energy striking it, it is impossible to optimize emitter material for wide ranges in wavelength (Trucchi, 2017).

Unfortunately, since emitters play the most considerable role in the conversion process, much of the existing research has been dedicated

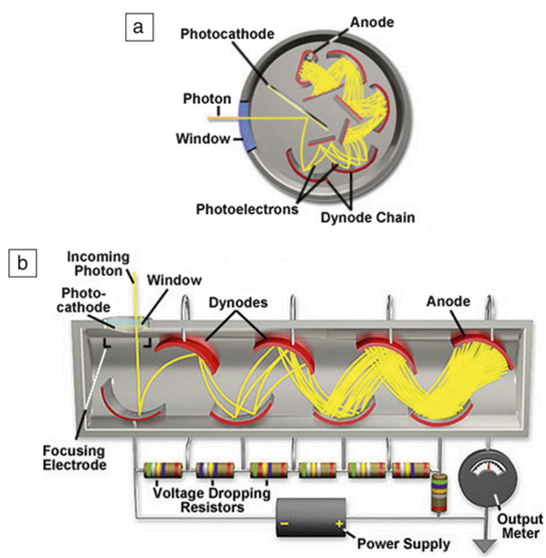


Figure 5: Common configurations for photomultiplier dynode chains; (a) side-on (b) tube (Trucchi, 2017)

to emitters. However, that does not mean no progress has occurred in the realm of collectors. We have an intermediate understanding of what requirements this component must fulfill. New materials and a more profound comprehension of the mechanisms that drive electron collection are currently being pursued and provide a strong direction for future research (Go, 2017).

We know from eq. 4 that maximizing power output means creating the greatest possible difference between the collector and emitter's work functions. This priority must be weighed against maintaining a relatively low work function for the emitter. Therefore, our work to discover new techniques to fabricate materials with lower work functions must continue to be aggressive. Collectors also play a vital role in TEC heat loss through two principal mechanisms. The first is through collecting electrons at levels above their own work function, meaning some electrons may receive more thermal energy than necessary to traverse the interelectrode gap and reach the collector successfully. This additional energy becomes wasted as the collector absorbs it and potentially risks preventing electrons from being collected. A suggested solution is to implement a grid-like structure near the collector surface to prompt tunneling into lower states before reaching the collector. The second is through the absorption of infrared light originating from the emitter. Incorporating materials with high infrared reflectivity can increase efficiency by minimizing the absorption of thermal radiation. Both these mechanisms result in the collector absorbing excess heat. If enough heat is absorbed, it can result in back emission, where the collector starts emitting electrons it has collected back into the interelectrode gap. This phenomenon can contribute significantly to space charge. Evidence suggests that choosing a surface material with a negative electron affinity (NEA) can help address this issue (Go, 2017; Abdul Khalid, 2016; Strohl, 2007; Trucchi, 2017).

Electron affinity refers to the energy changes that occur when an atom absorbs an additional electron and is typically the difference between the bottom edge of the conduction energy band and the vacuum level energy, as shown in figure 1. However, it is sometimes possible to design the vacuum level below the conduction band minimum, which would result in the shedding of energy by the collector instead of absorbing it. This reversal would promote more efficient electron collection, resolving the potential for back emission (Abdul Khalid, 2016).

Finally, lowering electrical resistance can reduce power loss, and evidence indicates that incorporating a high Richardson constant can help reduce electron reflectivity. However, due to uncertainties around the physics of emissions in novel materials with reduced dimensionality, new research should focus on any modifications to the Richardson-Dushman law that may be warranted. Additional focus areas should include developing comprehensive theory and simulation of collection and a database of materials and surfaces with complete theory, a deeper understanding of quantum tunneling and its role in emission-collection, and integrated collector designs that focus on nanostructures to facilitate tunneling (Trucchi, 2017).

Interelectrode Gap

Advancements in the design of the interelectrode gap have primarily served to combat the effects of space charge. Proposed solutions have revolved around either neutralizing the net charge across the region or manufacturing the distance between electrodes to be as small as possible (Go, 2017).

One approach to both aiding emission and neutralizing the accumulation of negative charge in the gap has been to fill it with a vaporized, ionized alkali metal (Swifter, 2018). This process is slightly different from the technique mentioned above of adsorbing vaporized alkali metals onto the emitter. Here, the metal is ionized beforehand, without giving that valence electron to the emitter's surface. Again, alkali metals' single valence electron makes them especially suited for this task. Cesium is often the element of choice because of its low ionization energy, around 3.9 eV. While the technique undoubtedly combats space charge and lowers the emitter's work function, it also has the unwanted side-effect of lowering the work function of every other surface it encounters. The inclusion of a reservoir for this ionized gas also places a limit on device lifespan. In their TOPAZ design, the Soviet Union approximated that a one-kilogram source of ionized cesium would have a lifespan of approximately one year. Additionally, the ionization process, which is performed by a low-voltage arc discharge, reduces converter efficiency by 30-50%. However, a recent study proposed further experimentation with a procedure requiring less energy input that combines a grid electrode and an applied magnetic field (Bickerton, 2017; Go, 2017; Abdul Khalid, 2016).

Another approach involves designing the interelectrode gap so small that there is not sufficient space for charge to accumulate, somewhere on the scale of five to ten micrometers (Swifter, 2018; Go, 2017; Trucchi, 2017). In addition to practical manufacturing challenges, at these distances, conduction also becomes an issue because of near-field radiative heat transfer. This phenomenon would grow by several orders of magnitude should the gap become too small. Russia experimented with a six-micrometer spacing design in 2001, but the converter ultimately proved mechanically unstable. Modern microfabrication, made possible by modular structures made of small emitter-collector assemblies, are currently being explored. They have remained stable for several hours at temperatures ranging from 900-1,400 Kelvin at distances of 100 micrometers (Go, 2017).

The use of spacers to minimize the gap and maintain a consistent distance between electrodes has been another strategy employed, utilizing several approaches. One test run managed a 1.6-micrometer gap using microbead-type spacers, while another design saw a ten-micrometer gap using silicon oxide spacers. Unfortunately, the latter still experienced large thermal losses through contact with the spacers, about 0.4 W/K. While this approach to resolving space charge has its own unique challenges, the possibilities for devices designed with microscale interelectrode gaps are enormous. We should expect to see further developments in this technique (Go, 2017).

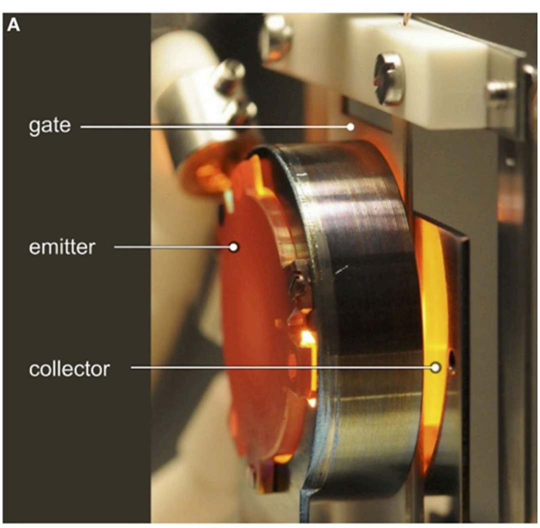
Interstitial gate electrodes have also been an exciting development that places a positively charged gate or grid in the collector-emitter space (Meir, 2013). Although this design requires wider spacing (~100 μm), imposing a potential of about 5-10 V makes it possible to facilitate electron passage and prevent potential electron clouds. However, gate currents, which refers to the positively charged gate siphoning electrons, must be suppressed, either by applied magnetic fields (~0.5 T) or electron-transparent gate materials (Abdul Khalid, 2016; Wanke, 2016). The latter of the two could help contribute to the design of converters of minimal weight. This direction is promising, as it offers the possibility of tunable devices, adjusting parameters such as output power and cathode temperature. Also, larger interelectrode gaps provide increased durability and extend operational lifespan (Go, 2017).

Nevertheless, while models predict high-efficiency levels, as seen in figure 6b, further validation through experimentation is still needed. While current density is related to gap distance, it is also dependent on the width of the holes in the gate. While the highest-measured efficiencies are when both emitter-collector and gate holes are at their smallest, agreeing with predictions, fabrication and assembly continue to pose challenges in execution (Go, 2017; Mannhart, 2014).

Applications

One could certainly argue that its broad applicability has been the driving force behind the ample amount of research poured into thermionic conversion. With their simplistic design, high potential efficiency, low maintenance, and long lifespan, TECs can address a diverse set of needs. They have been studied extensively, theoretically, in three leading contexts: as cogenerators, as parts of topping cycles, and as complete replacements for existing power suppliers (Go, 2017). As complete power source replacements, TECs are most adequately suited for space. In conditions that often occur millions of miles away from Earth with the Sun acting as the only energy source, TEC's small design with virtually no maintenance requirements, paired with its compatibility with photoemission enhancement, all but guarantee ideal performance. In 1987, the Soviet Union launched two 5 kW nuclear-powered TEC's aboard experimental satellites (Go,2017; Abdul Khalid, 2016).

Their roles in topping cycles position them in more complex energy-producing systems for efficiency purposes, contributing to larger-scale applications. Possible options include steam turbines at electrical and nuclear power plants and solar farms. Rasor Associates performed early research within this context in the 70s as



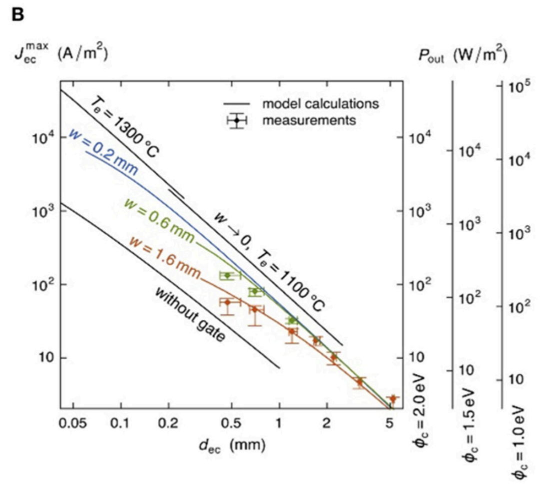


Figure 6: (a - left) Image of a thermoelectric converter using a positively charged gate in the collector-emitter gap; (b - above) Graph showing current density over gap spacing Go, 2017). Adapted from Meir et al (2013) https://aip.scitation.org/doi/10.1063/1.4817730 under CC BY 3.0.

the U.S. was exploring nuclear energy. Their study suggested employing TECs as topping cycles with fusion reactors could increase plant efficiency by almost 6% and generating efficiency by 27.6%. Preliminary data has also shown that in combination with diesel and gasoline combustion, integrating TECs provide benefits over internal combustion alone (Abdul Khalid, 2016).

However, TEC's most residentially relevant application is probably as cogenerators. We are beginning to see private companies rising to this opportunity. In the '90s, a research group from Russia and the Netherlands designed a domestic boiler system that was available commercially. It produced about 1.5 kW of energy (Abdul Khalid, 2016). In Bothell, WA, a company called Modern Electron offers compatible homeowners an electrical substitution to dependency on current power grid infrastructure. Their device design, the details of which are not published, works in partnership with natural gas. 160,000 homes across the U.S. and Europe use natural gas to heat their homes and water. The TEC Modern Electron has produced integrates with a home's water heater or furnace. A pilot light can burn at over 2,000 °C while only heating water to about 80 °C (Chao, 2016). The rest of that energy is wasted. Modern Electron claims to have increased conversion efficiency by a factor of ten and lower operating temperature for emission, granting independence from the power grid, hundreds of dollars in annual savings, and decreasing the average home's carbon footprint by 1.19 pounds annually (modernelectron.com). In 2015, they secured $10 million in funding and were recognized by Seattle as one of fifty start-ups to watch in 2019 (Osborn, 2019). With that level of traction, it is only a matter of time before we see competitors enter the market. TECs clearly have a promising future as cogenerators.

Conclusion

The thermionics community has invested extensive research in energy conversion technology. That investment was not frivolous. With the evolving energy demands of the planet and the existential consequences we face from excess burning of fossil fuels, thermionic emission is a promising option. The world needs simple solutions. While the physics behind emission itself is not simple, leaving many questions left to answer, the technology's application is. Energy is challenging to produce in the same place we are using it (Chao, 2016). Many developing countries across the globe face this exact problem. TEC's ability to capitalize on waste heat, regardless of its source, offers an auspicious option for those communities. For developed nations, efficiency is what frequently drives improvement. TEC's ability to work in conjunction with other energy producers provides a valuable opportunity to take full advantage of the resources we consume. Moreover, in practically every scenario, their simple design, minimal maintenance requirements, potential high efficiency, and compact design outbid many other options. TECs are not going anywhere and have the potential to become the backbone of sustainable energy production solutions; their research must continue.

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