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Parametric Design and Performance Evaluation of Irreversible Planar Thermal Electronic Energy Converter

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Abstract. Electricity may be generated in a highly efficient manner from heat of various sources by means of thermionic energy converters (TICs). However, the potential of this energy conversion technology is always hindered by the space charge effect, which drastically reduces the electron transport within this converter. To overcome this challenge, external fields like electric and magnetic fields are incorporated to mitigate the effect of space charge in TICs. In this paper, an irreversible thermionic energy converter model utilizing these external fields, namely the thermal electronic converter (TEC), is proposed. The model of the TEC consisting of an accelerating gate, an emitter, and a collector is proposed, in which the various heat losses and thermal radiation are taken into account. A formula for the overall efficiency of the system is analytically derived. For given values of the ratio of the front surface area of the absorber to that of the emitter and the vacuum gap between the emitter and the collector, the operating temperatures of the emitter and collector are determined by solving the energy balance equations. The maximum efficiency of the TEC is calculated for given values of the work functions of the emitter and collector materials, and some key parameters such as the net current density of the TEC, operating temperatures of the emitter and collector, vacuum gap between the emitter and the collector, and area ratio of the absorber to the emitter are optimally determined. Furthermore, the effects of the work functions on the performance of the TEC are discussed, and several parametric selection criteria are obtained. This study provides a comprehensive parametric design and performance evaluation of the TEC, offering insights into optimizing its efficiency for practical applications.

1. Introduction

Thermonic energy converters (TICs) has been recognized as one of the potential candidates for replacing conventional energy conversion system due to their ability to operate at high temperatures, typically between 1200-1400K [1]. However, these high operating high operating temperatures lead to significant heat losses and irreversibilities, which have historically limited the efficiency of thermionic devices. Additionally, the performance of these devices is severely constrained by the space charge effect [1,6]—a phenomenon where emitted electrons form a negatively charged cloud in the inter-electrode space, repelling subsequent electrons and thus reducing the current density and overall efficiency of the converter as depicted in Figure 1.

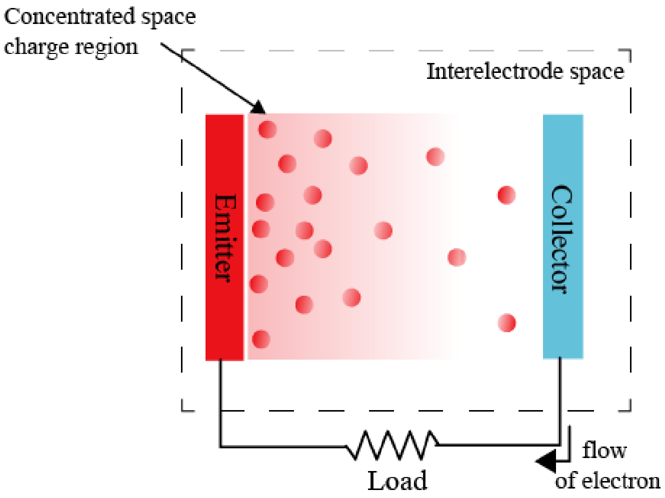

Figure 1. Diagram of space charge formation in thermionic energy converter

The space charge effect has been one of the most significant challenges in advancing the efficiency of thermionic energy converters (TICs) [1,2]. Traditional approaches to mitigate this effect have included introducing positive ions into the inter-electrode space [2], minimizing the gap between the emitter and collector [3], and developing materials with lower work functions [4]. Despite these efforts, the issue persists, hindering the practical application of TICs. In response to these challenges, the concept of thermal electronic energy conversion (TEC) was introduced. This approach seeks to reduce the space charge effect by incorporating external electric and magnetic fields into the converter design [5]. The TEC method leverages an electrostatic field generated by a gate electrode to pull electrons away from the dense space charge region, while a magnetic field is used to guide these electrons towards the collector. This dual-field approach not only mitigates the space charge effect but also enhances electron transport efficiency, thereby improving the overall performance of the device[6].

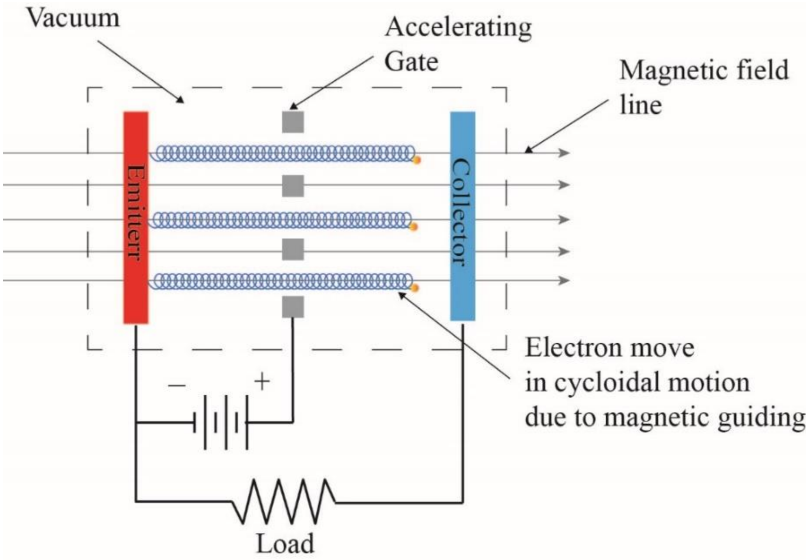

Figure 2. Schematic diagram of combined magnetic and electrostatic triode TIC concept so called thermal electronic energy conversion [5]

While there has been considerable progress in the theoretical development of TECs, there remains a need for detailed parametric analysis and performance evaluation of these devices, particularly in planar configurations. This paper addresses this gap by conducting a comprehensive study on the parametric design and performance evaluation of a planar TEC. By exploring the effects of various design parameters, such as electrode geometry, work function, and field strength, this research aims to optimize the efficiency and output power of TECs, providing valuable insights for their practical implementation in high-temperature energy conversion applications

2. System Analysis of Planar Thermal Electronic Energy Converters

The schematic diagram of planar TEC operating between two heat reservoirs is shown in Figure 1. It consists of two parallel electrodes plates with vacuum gap between and electrodes and an grid-like accelerating gate between the two electrodes. The emitter of the parallel plate TEC receives heat from the higher temperature heat reservoir maintained at temperature, T_H . The collector release heat to the lower temperature heat reservoir maintained at temperature, T_L. The temperatures of emitter and collector were determined by deriving energy balance equation using first law of thermodynamics. To generalize this analysis, the heat exchange between the electrodes and heat reservoir is considered to obey Stefan-Boltzmann's law of radiation. Without the addition of the gate, the thermal radiative heat transfer from emitter to the collector can be expressed using the Stefan-Boltzmann equation:

$$Q_{rad,E\_C} = F_{E-C}A_{E-C}\sigma\,\varepsilon({T_E}^4 - {T_C}^4) \qquad (1)$$

where F_{E-C} is the view factor between emitteer and collector, A_{E-C} is radiation heat-exchanging area between emitter and collector, σ is Stefan-Boltzmann constant, ε is the thermal emissivity of the electrodes which typically equals to 0.1 [2].

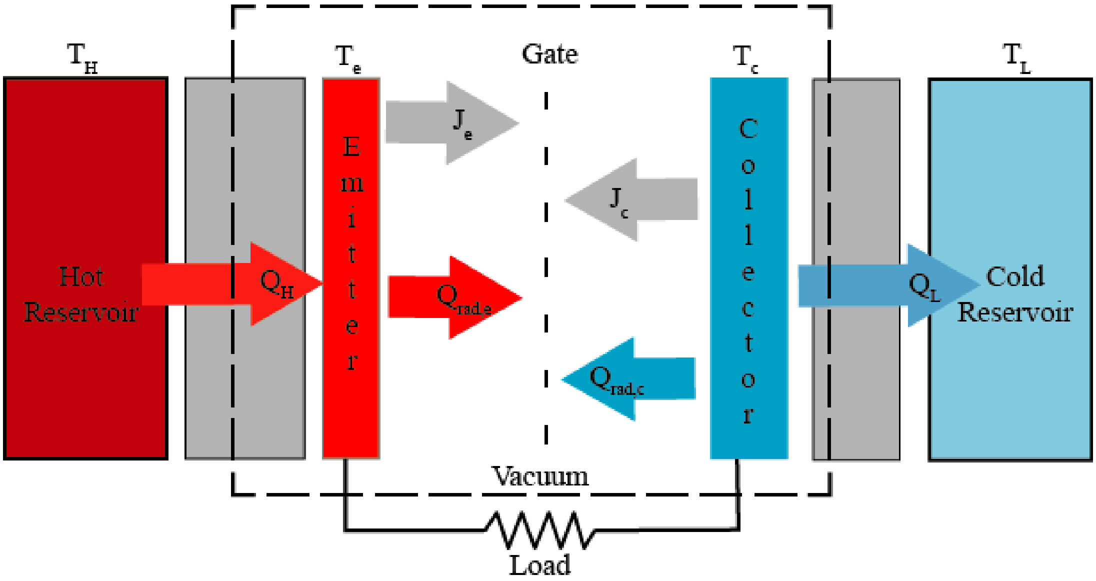

Figure 3. Schematic diagram of a parallel plate TEC (PTEC)

Theoretical efficiency of any energy converter is defined as the ratio of the output power across the load P_L to the total heat input to the emitter, Q_H

$$\eta_{TEC} = \frac{P_L}{Q_H} \qquad (2)$$

Neglecting the space charge potential as it is assumed to be suppressed by the incorporation of electric field and magnetic field, the potential difference or the voltage can be defined as:

$$V = \frac{\phi_e - \phi_c}{e} \tag{3}$$

where ϕ_E and ϕ_C is the work function of the emitter and collector respectively and e is the elementary charge of electron. For a planar TEC, electric field is used to accelerate the electrons away from the emitter to the collector. In order to sustain the electric field, some power is used. The power loss due to gate electrode is defined as:

$$P_g = J_g V_g \tag{4}$$

P_g must be directly subtracted from the produced output power across the load, P_L. Thus, the efficiency of the planar TEC becomes:

$$\eta_{PTEC} = \frac{P_L - P_g}{Q_H} \tag{5}$$

The dimensions of the opening of the gates contributes to the transparency of the gate which ranges from $0<\tau<1$. The incorporation of the gate reduces the transfer of current and thermal radiation across the interelectrode gap. Thus, the net current density, J_{net} transported to the collector through the load becomes:

$$J_{net} = \tau J_e - J_c \tag{6}$$

Hence, the power loss on the gate per unit area becomes:

$$P_g = V_g J_g = V_g(1-\tau)(J_e + J_c) \tag{7}$$

In equilibrium, the heat input to the emitter Q_H is equal to the sum of all the heat loss from the emitter where Q_{rad} is the heat transfer due to radiation from the emitter, Q_{el} is the electron emission cooling and Q_{cond} is the conductive heat transfer through the emitter lead.

$$Q_H = Q_{rad} + Q_{el} + Q_{cond} \tag{8}$$

The conductive heat transfer loss through the lead Q_{cond} is difficult to calculate theoretically but as a conservative approximation, it can be taken to be 30% of the other thermal loss mechanism in this analysis. The gate modifies the heat loss from the emitter due to thermal radiation in the same way as it modifies the current:

$$Q_{rad,E\_C} = F_{E-C} A_{E-C} \sigma\, \varepsilon (T_E{}^4 - \tau T_C{}^4) \tag{9}$$

The evaporation or cooling due to emission of electron becomes:

$$Q_{el} = \frac{J_e}{e}(\phi_e + 2k_B T_e) - \frac{\tau J_c}{e}(\phi_e + 2k_B T_C) \tag{10}$$

The general expression for heat-to-electricity of planar TECs is given as:

$$\eta_{PTEC} = \frac{J_{net}\left(\frac{\phi_e - \phi_c}{e}\right) - V_g(1-\tau)(J_e + J_c)}{Q_{rad} + Q_{el} + Q_{cond}} \tag{11}$$

In the parametric design and performance analysis of the thermoelectronic energy converter (TEC), two critical parameters are the gate voltage (V_g) and the transparency of the gate (τ).

Table 1. Parameters used for parametric analysis of planar TEC.

Specification	Value
Gate voltage, V_g (V)	5.0
Gate transparency, τ	0.8
Collector workfunction, ϕ_c(eV)	1.0
Collector temperature, T_c(K)	300

3. Result and Discussion

The efficiency of heat-to-electricity conversion in the planar TEC was evaluated by developing energy balance equations for both the emitter and collector electrodes, incorporating the effects of a gate placed in the middle of the interelectrode gap. The three-dimensional plot in Figure 4 shows the relationship between the efficiency of the planar TEC, the voltage difference (V), and the collector work function (ϕ_c).

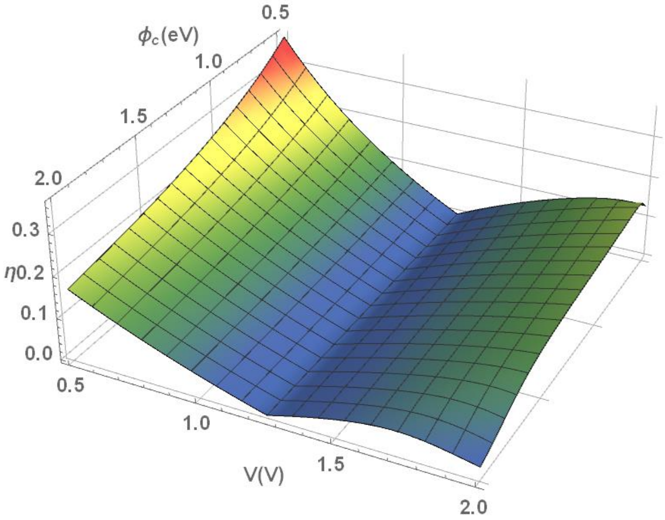

Figure 4. Three dimensional graph of efficiency varying with voltage and collector work function for planar TEC with V_g=5V and τ=0.8

The graph clearly demonstrates that the efficiency is highly sensitive to the work functions of both the emitter and the collector. Maximum efficiency is achieved when the collector work function is at its lowest, combined with a minimal difference between the work functions of the emitter and collector. This indicates that to achieve optimal power output and high conversion efficiency, both electrodes should possess low work function values. Notably, the graph reveals a local minimum in efficiency at a voltage (V) of approximately 1.25V. This phenomenon can be attributed to the specific configuration of the planar TEC, where the electrodes are positioned face-to-face. At this voltage, the ratio of current emission from the emitter and the collector produces the lowest net current density while maximizing the heat transfer ratio. Consequently, the back emission is highest at this point, reducing the overall efficiency. Figure 5 depicts the power output of the planar TEC as a function of the collector work function (ϕ_c) and the voltage difference (V) between the emitter and collector.

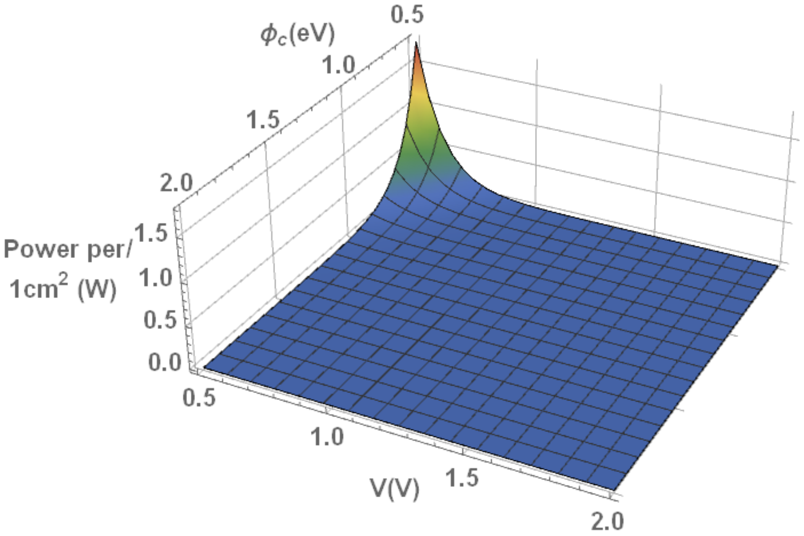

Figure 4. Three dimensional graph of efficiency varying with voltage and collector work function for planar TEC with V_g=5V and τ=0.8

The analysis shows that as the work functions of both the emitter and collector decrease, the power output increases. This is because lower work functions allow more electrons to acquire sufficient energy to escape from the emitter surface, thereby increasing the current density. Similarly, a lower collector work function facilitates easier electron absorption by the collector, further enhancing the net current density and, consequently, the power output of the device. Figure 6 presents the calculated efficiency of the planar TEC as a function of the emitter temperature (T_e) for a series of emitter work functions, while keeping the collector work function constant at $\phi_c = 1.0$ eV and the collector temperature (T_c) at 300K.

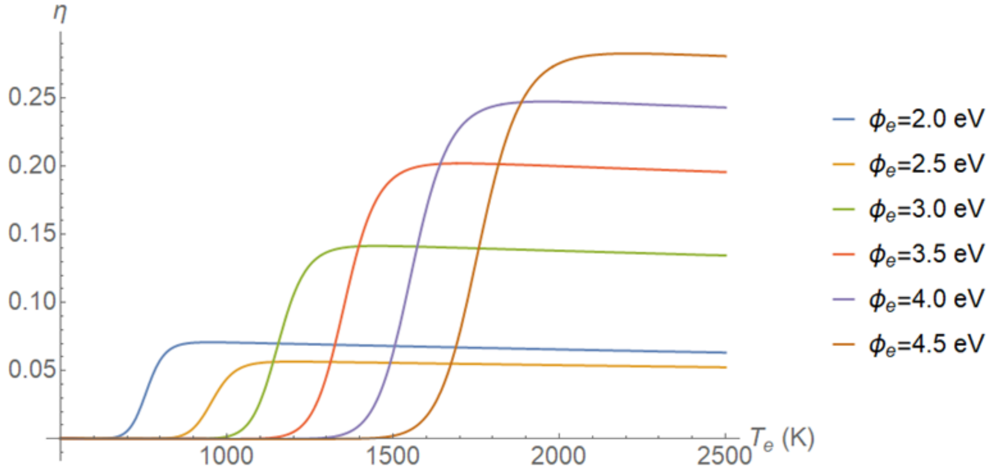

Figure 6. Calculated efficiency of a planar TEC as a function of the temperature of emitter for a series of emitter workfunction with constant collector workfunction and temperature, ϕc at 1.0eV and Tc at 300K

The plot in Figure 6 indicates a complex relationship between the emitter work function and efficiency. Specifically, there is an initial decrease in efficiency when the emitter work function increases from 2.0 eV to 2.5 eV, followed by a subsequent increase as the work function continues to rise up to 4.5 eV. The observed dip in efficiency at $\phi_e = 2.5$ eV mirrors the behavior seen in the voltage-dependent efficiency graph (Figure 4), where the efficiency reaches a local minimum at a specific voltage. This effect is likely due to the heightened heat transfer between the facing electrodes at this particular work function, which reduces the net current density and, in turn, lowers the device's overall efficiency. However, as the emitter work function increases beyond this point, the efficiency improves, driven by the higher emitter temperature. This leads to an increased electron density while maintaining constant back emission, ultimately enhancing the efficiency of the conversion process.

4. Conclusion

This paper presents a comprehensive parametric design and performance analysis of a planar thermal electronic converter (TEC), focusing on the effects of work function, gate voltage, and emitter temperature on the efficiency and power output of the device. The study highlights several key findings that contribute to the understanding and optimization of thermal electronic energy conversion systems.

First, the results indicate that the efficiency of the TEC is highly dependent on the work functions of both the emitter and collector electrodes. To achieve optimal performance, it is crucial that both electrodes possess low work function values, which facilitates greater electron emission and absorption, thereby enhancing the overall current density and conversion efficiency. tabulated.

Furthermore, the analysis shows that the TEC's efficiency is also influenced by the emitter temperature. As the emitter temperature increases, the electron density rises, leading to an improvement in efficiency, particularly when the work function of the emitter is optimized.

Overall, this research demonstrates that by carefully adjusting the key parameters—such as the work functions of the electrodes, gate voltage, and emitter temperature—it is possible to significantly enhance the performance of thermal electronic converters. These findings offer valuable insights for the design and development of more efficient TECs, paving the way for their practical application in high-temperature energy conversion systems.

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