Advanced Thermionic Energy Converters: Enabling Technology for Low Greenhouse Futures

Investigators
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Introduction

This research involves the study of the use of diode laser excitation to alter/enhance the production of cesium (Cs) ions in the gap of a Cs-filled ignited (arc) or unignited Thermionic Energy Converter (TEC). Continuous-wave laser energy addition tuned to an excited electronic transition in Cs is used to "inject" ions/plasma at levels sufficient for space-charge neutralization of the electron stream emitted by the thermionic cathode. Such volume production eliminates the need for thermionic ion production at the cathode surface (in so-called unignited TECs), and/or electron collisional ionization within the gap (in so-called ignited or "arc" mode TECs). In some ways, this laser-ion injection is similar to an ion injection "triode" TEC configuration which is considered state-of-the art in TEC design, but is free of the complexity of the later, not requiring an immersed, electrically-heated grid. In addition to increasing TEC efficiency (as it is postulated that the cost of ionization using optical excitation can be less than that in either a triode or an arc-mode TEC), the optical excitation can be modulated to produce a corresponding modulation in output TEC current, greatly facilitating power conditioning. This modified TEC can be thought of as an advanced heat engine, and if the efficiency can be made sufficiently high, can serve as a topping cycle for combustion and solar energy conversion systems. A schematic (qualitative) illustration of the current-voltage response of the laser-assisted TEC operation, and its comparison to ideal and arc-ignited TEC performance is shown in Fig. 1.

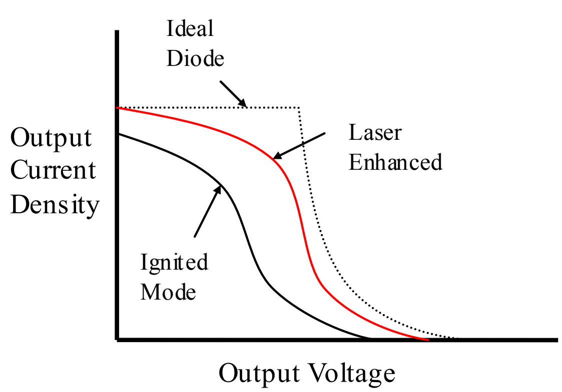

Figure 1: Comparison of ideal, ignited mode, and laser enhanced current-voltage characteristics

Background

The exploratory phase of this research is aimed at (i) understanding the potential role, through systems analysis, that advanced TECs can play in these energy conversion technologies, (ii) developing the energy budgets related to the production of Cs-ions using quasi-resonance laser ionization at vapor pressures commonly encountered in Cs-filled TECs, (iii) the formulation of models for the quasi-resonance ionization process and a coupled one-dimensional model of the TEC, and (iv) the design of a laboratory-scale Optically-Modulated Thermionic Energy Converters (OMTEC) for experimental model validation in subsequent follow-on projects.

During the past four months, we have made progress on three fronts. We have developed a particle-in-cell (PIC) model of a planar diode discharge, operating on argon, which will ultimately become a PIC simulation of an OMTEC operating on Cs. This model will allow us to simulate the current-voltage characteristics of an OMTEC with and without laser-induced cesium ionization. Simultaneously, we have completed the first stage of a MATLAB model of overall thermionic converter performance under certain simplifying assumptions. Finally, we have completed the design of a laboratory (OMTEC) test cell which will eventually be fabricated, in a subsequent funding period, to provide experimental validation of thermionic converter performance and its response to laser-induced cesium electron heating and ionization. It is noteworthy that following the submission of our proposal, we discovered a brief report on work in Japan that demonstrated that substantial improvement in TEC current density using pulsed *resonance* ionization in cesium [1]. In the performed experiment, the radiation was produced by a pulsed laser at a wavelength of 852 nm, increasing the short circuit current to near the saturation current density (ideal), and therefore indicating nearly complete space charge neutralization. This process was considered in our original proposal, but we believe that our quasi-resonance continuous wave (cw) laser approach is much more efficient, and more practical, as it can be implemented with a very inexpensive diode laser. Nevertheless, these Japanese studies have paved the way towards further research, and have partially validated our proposed concept.

Results

Particle-in-cell – Monte Carlo Model

A simple particle-in-cell - Monte Carlo (PIC-MC) model has been developed. The model is one dimensional in physical space and tracks velocities in three dimensions (1D-3V) [2]. The model assumes two boundaries of an infinite-sized flat surface. Although the model is geometrically simple, one dimensional models have been employed as effective tools for understanding physical phenomena in discharges, including thermionic discharges with interesting dynamical behavior [3, 4]. The model tracks particle movement by employing weighted sample particles representing a large number of atoms (number of pseudo-particles is 10^4-10^6). The MC method allows us to include further collisional mechanisms and/or laser excitation mechanisms in a relatively straightforward way.

So far, we have developed a base code, which can simulate direct-current (dc) glow discharges. The basic model includes elastic, excitation, and ionization collisions for electron-neutral interactions, and elastic and charge-exchange collisions for ion-neutral interactions. We have tested the model against well-studied argon (Ar) dc discharges with cross section data set provided by Phelps [5, 6]. Figure 2 shows examples of simulated plasma (ion and neutral) density distributions for Ar discharges (p = 1 Torr and d = 5 mm). The discharge voltages are 300 and 600 V and a secondary electron emission coefficient of 0.1 was taken for the current condition at the cathode. Sheath formation is easily captured, plasma densities are in the range of $\sim 3\times10^{17}$ to $\sim 13\times10^{17}$ m^{-3}, and discharge currents are ~19 Am^{-2} and ~68 Am^{-2} for 300 and 600 V, respectively. These voltage-current characteristics agree well with those seen experimentally [7], providing a measure of confidence in the base model. The model is undergoing refinement to (a) include thermionic emission, (b) include Cs kinetics, and (c), include quasi-resonance laser-excitation kinetics.

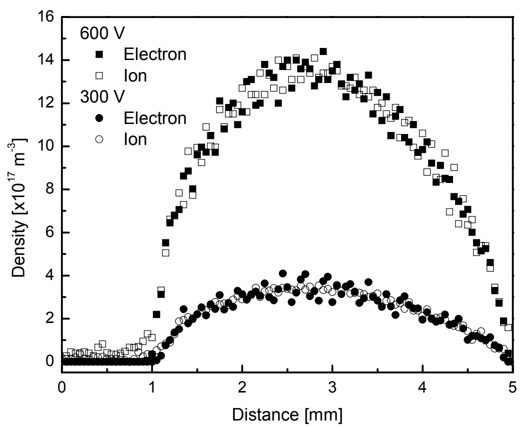

Figure 2: Plasma density distributions simulated for Ar 1 Torr discharges. The left side (0 mm) is 0V and the right side (5 mm) is 300 or 600 V. The secondary electron emission coefficient was 0.1.

OMTEC Test Cell Design

An experimental apparatus for the OMTEC has been designed. A schematic of the test cell is shown in Fig. 3, and a magnified view of the emitter and collector are shown in Fig. 4. The design of the test cell is based on that of Rasor [8]. The tungsten emitter and nickel collector are supported by alumel and chromel leads, which allow temperature to be measured thermoelectrically. The emitter temperature is also measured independently with an optical pyrometer. In addition, the alumel leads of the emitter and

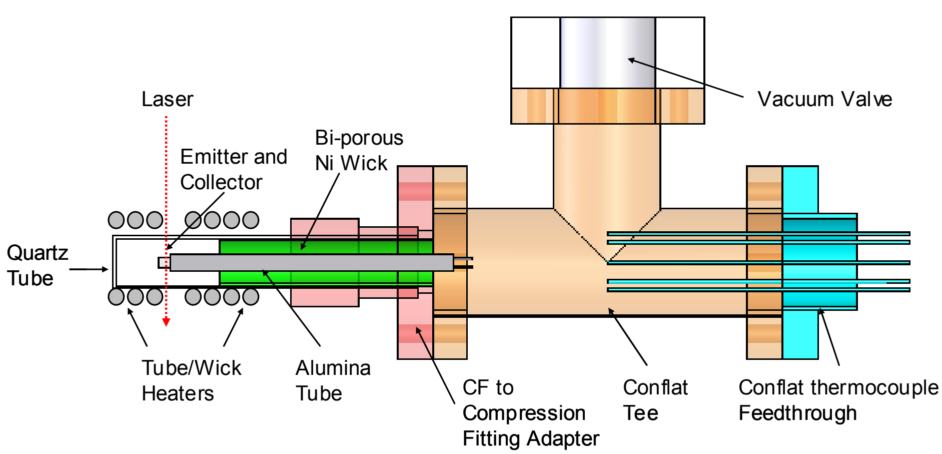

Figure 3: OMTEC Test Cell

collector are connected through an external voltage source and ammeter to measure the current-voltage characteristics of the converter. The four leads to the emitter and collector protrude from a four-hole alumina tube (4 in. long, 0.2 in. outer diameter). On the opposite end of the tube, the leads are connected to four pins of a conflat thermocouple feedthrough.

The low pressure (~.01 – 1 Torr) environment for the thermionic diode is provided by the combination of a mechanical and turbo pump. The pumps are connected to a valve, which is in turn connected to a conflat tee (2 ¾ in. nominal diameter). The tee is also connected to the thermocouple feedthrough, as well as to a conflate-to-compression-fitting adapter. The compression fitting is provided by a ¾ in., viton O-ring seal. Mounted in the compression fitting is a single-ended fused quartz tube (4 in. long, with ¾ in. outer diameter and 1 mm. thick wall).

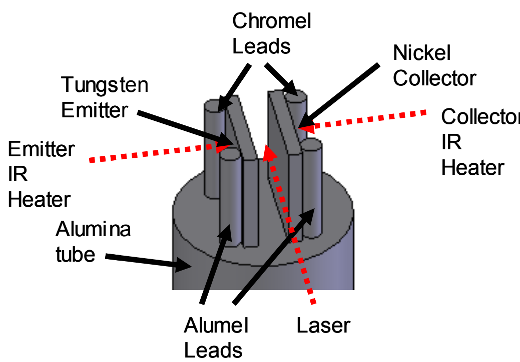

Figure 4: Electrode Assembly, IR heaters, and Laser

Fused quartz was chosen for the TEC envelope for its excellent optical transmission properties, with over 90% transmittance for wavelengths between 280 nm and 3000 nm. As a result, the laser (601 nm) will pass relatively unimpeded through the tube. Furthermore, the emitter and collector may be heated to temperatures in excess of 1500 K and 750 K, respectively, by their own radiation sources (commercially available).

Cesium vapor is maintained in the thermionic-diode region via a bi-porous nickel tube heat pipe (3 in. long with 0.55 in. outer diameter and 1 mm thick wall) which is soaked with 1 gram of liquid cesium prior to test cell assembly. The end of the nickel tube nearest to the thermionic diode is heated by a Ni-Cr wire heater external to the fused quartz tube. Ni-Cr heaters are also used to heat the diode region of the test cell, preventing cesium condensation on the inner surface of the quartz tube. In this manner, cesium evaporates from the heated end of the nickel tube and condenses on the cooler end, close to the compression fitting, which is maintained near room temperature. The nickel tube then wicks the condensed cesium back to the heated region, to repeat the cycle. The temperature of heated end of the nickel wick determines the pressure of cesium in the thermionic diode region of the test cell.

A 1-kilogauss magnetic field is applied perpendicular to the surfaces of the emitter and collector via external magnetic coils to confine the discharge to the interelectrode region. Experimental simplicity and precise control are insured by the use of radiation sources for heating of the emitter and collector and ionization of the cesium. In this manner, the test cell may undergo the complete set of experimental trials without having to be exposed to air. The parameters which will be varied between trials are emitter temperature, collector temperature, and cesium vapor pressure. In each trial, the intensity of the cesium ionization laser will be varied to determine its effect on the current-voltage characteristics of the diode under the given conditions.

Energy Systems Analysis

Two thermodynamic systems models are being developed as part of the project: a solar-Stirling engine and a conventional combustion system, each with a TEC topping cycle. The high emitter and collector temperatures, ~2000 K and ~1000 K, respectively, allow for high overall Carnot efficiencies when the TEC is added as a topping cycle.

The solar-Stirling system with TEC topping cycle is shown in Fig. 5. A parabolic dish provides concentrated radiation to heat the emitter directly, and the collector of the TEC exhausts waste heat to a Stirling heat engine at its optimum working fluid temperature (~1000 K). In this manner, the combined system can potentially yield a higher power output and efficiency relative to the solar-Stirling parabolic dish systems currently in existence.

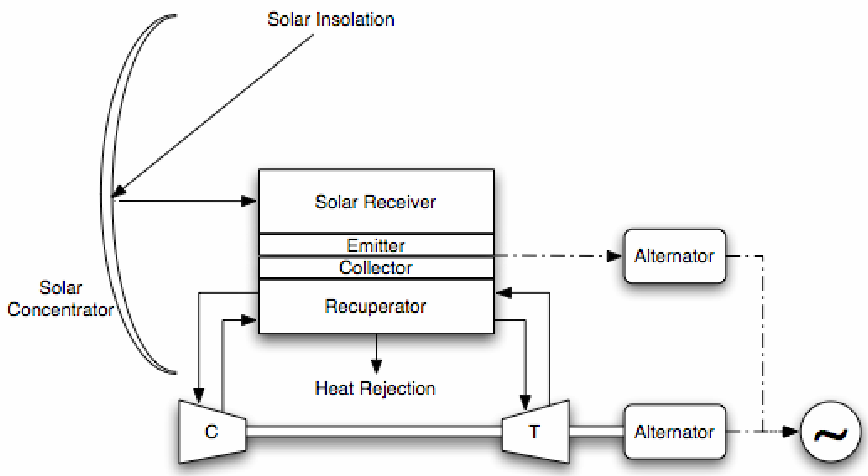

Figure 5: Solar-Stirling parabolic dish with TEC topping cycle

An example of a combustion-heated system (in this case a STIG turbine-Rankine combined cycle with TEC topping cycle) is shown in Fig. 6. An isothermal staged combustor heats the emitter, and a liquid water spray holds the collector temperature down. The vaporized water is then injected into the combustion products to cool them slightly before expanding across a turbine. The hot exhaust gases then drive a Rankine bottoming cycle. The use of water as moderator for the combustion cycle allows larger fuel flow rates, and thus higher power density from the system. The hope is that with the TEC directly taking a portion of the exergy for electricity while capturing and reusing the waste heat downstream, the system can operate at very high efficiencies as well.

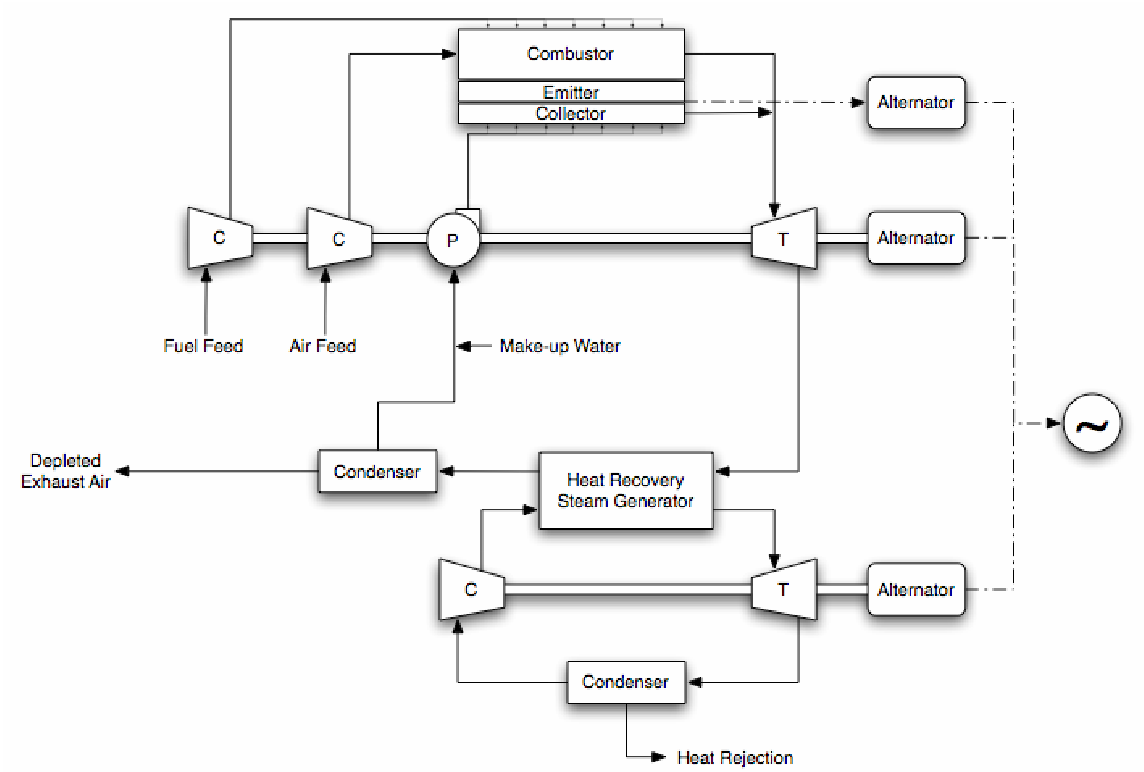

Figure 6: Steam-injection gas (STIG) turbine-Rankine combined cycle with TEC topping cycle

Progress

Because thermionic converters have potentially high efficiencies (~25%) and potentially high power densities (~100 Watts cm^{-2}), and because they operate with high temperature heat sources and heat sinks (which allows for their use as topping cycles to increase overall efficiency of energy systems) the possible impact on carbon emissions is enormous. If incorporated into solar-Stirling systems, TECs have the potential to increase power output at a low added cost, resulting in a decrease in cost of carbon-free energy. Incorporation into widespread conventional combustion systems will allow for higher efficiencies to be achieved, reducing carbon emissions.

Future Plans

Particle-in-cell – Monte Carlo Model

We have recently begun to include thermionic electron emission from a hot electrode and are simulating thermionic discharges as reported in previous studies [3, 4]. Other features we plan to add to our model in the immediate future are: (a) a neutral species calculation, whose MC model has been already developed and employed successfully to the analysis of Ar dc discharges [9], (b) inverse collisional processes, such as superelastic collisions, (c) contact ionization on a hot surface, (d) the excitation process by laser induction, and (e) background temperature elevation by power deposition.

OMTEC Test Cell Design

The design will be further refined, and the required parts will be procured. Time permitting, preliminary operation will be examined, although without optical modulation, to reproduce the findings of Rasor [8]. It is anticipated that extensive experimental studies will be carried out in a continuation grant.

Energy Systems Analysis

Complete models of the solar-Stirling system with TEC topping cycle and combustion-heated combined cycles with TEC topping cycles are under construction. Eventually these models will be able to thoroughly approximate the overall system efficiency and power output with a given TEC efficiency. These models will be compared to models which lack the TEC topping cycles, as well as to data from combustion-heated combined cycle power generators currently in existence.

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