Thermionic Energy Converter System Using Heat Flux in Divertor Region

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We have investigated the feasibility of a thermionic energy converter (TEC) system using the high heat flux from divertor plasmas in fusion devices. If the kinetic energy of particles can be converted to electricity by using a TEC, the efficiency of fusion reactors could be improved. The basic properties of the TEC were analyzed by a two-dimensional particle-in-cell simulation, including the current-temperature characteristics and potential profile between the electrodes and the magnetic field effect. Verification experiments on the TEC system under divertor-relevant conditions were also conducted in the Active Cooling Test device, in which the heat load is produced by an electron beam.

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1. Introduction

In fusion devices, divertor plates are exposed to high heat and particle fluxes that are released from the core plasma. In the future, the high heat flowing into the divertor is expected to represent 20% of the power released from the plasma. A cooling method using helium gas is being discussed for the reduction of the heat flux. However, this method remains to be established and requires further research. The thermionic energy converter (TEC), which converts the heat energy directly into electrical energy, is an alternative. If the kinetic energy can be converted to electricity by using a TEC, the efficiency of fusion reactors could be improved.

The TEC has been studied over a long time for application to nuclear thermionic power generators in spacecraft and combustion-heated thermionic power systems [1, 2]. The advantages of the system are its high theoretical efficiency and simple configuration. The TEC system has a non-mechanical gaseous electronic device for converting heat directly into electron emission [2]. Although the efficiency of the ideal TEC at practical power densities is approximately 60% of the Carnot thermodynamic limit, it is higher than that on present application devices, which is approximately 25%–35% of the Carnot efficiency [2]. A detailed estimation of the efficiency is available elsewhere [3]. Recent studies of the TEC focused on material research of the electrodes [1].

In this paper, verification experiments of the TEC under fusion-relevant conditions were performed using the Active Cooling Test device (ACT) for heat load testing. Prior to the experiment, the fundamental properties of the system were investigated by a particle-in-cell (PIC) simulation.

2. Principle and Theoretical Efficiency of Thermionic Energy Converter

2.1 Thermionic energy converter system

Figure 1 illustrates the principle of the TEC system. First, we set plane parallel electrodes in vacuum, and placed an external load between the emitter (work function \( \phi_E \)) and the collector (work function \( \phi_C \)). Then, the emitter is heated with the heat flux from the divertor plasma and releases thermionic electrons from its back side. The thermionic electrons are accelerated by the potential difference between the electrodes (\( \Delta \phi = \phi_E - \phi_C \))[1, 2]. Finally, the collector collects the thermionic electrons; consequently, current flows through the electrode, and electric power can be extracted from the external load.

The motive diagram in Fig. 2 (a) shows the potential energy of an electron as it moves from the emitter to the collector when the voltage drop due to the external load is zero [1, 2]. This situation is called the ideal mode. Figure 2 (a) indicates that we should select a large work function material for the emitter, e.g., tungsten (\( \phi_W = 4.5 \text{ eV} \)) and a small work function material for the collector, e.g.,...
Fig. 1 Thermionic energy converter system.

Fig. 2 Potential profile between the emitter and the collector. (a) Motive diagram for the ideal diode TEC. (b) Potential profile with virtual cathode.

Thoriated tungsten ($\phi_{Th-W} = 2.6$ eV) or LaB$_6$ ($\phi_{LaB_6} = 2.6$ eV). All the electrons arrive at the collector when the potential profile is as shown in Fig. 2 (a). However, the potential profile is usually not like that shown in Fig. 2 (a) because electrons have an electric charge and modify the profile. Furthermore, the current flow through the external load decreases the potential difference between the electrodes.

Thermionic electron emission is expressed by the Richardson-Dushman equation as

$$J_0 = AT_E^2 \exp \left( -\frac{e\phi_E}{k_B T_E} \right),$$

(1)

where $A$ is a coefficient called the Richardson constant in A/(m$^2$ K$^2$), which depends on the material, $T_E$ is the emitter temperature in K, $k_B$ is the Boltzmann constant in J/K, and $e$ is the elementary electric charge in C. The space charge limited current is expressed by the Child-Langmuir equation as

$$J = \frac{4\varepsilon_0}{9d^2} \left( \frac{2e}{m_e} \right)^{1/2} V^{3/2},$$

(2)

where $\varepsilon_0$ is the dielectric constant in vacuum in F/m, $d$ is the distance between the emitter and the collector in m, $m_e$ is the mass of an electron in kg, and $V$ is the voltage difference between the electrodes in V. If the voltage drop due to the external load is neglected, $V = \phi_E - \phi_C$. The electron emission current, $J_0$, is an exponential function of $T_E$, as shown in Eq. (1). On the other hand, the flowing current, $J$, varies as the inverse of $d^2$ and increases with $V$.

The flowing current is limited owing to the space charge effect expressed by the Child-Langmuir equation. When the emitter releases many thermionic electrons, the electrons pile up near the emitter and produce a potential dip called a virtual cathode, as shown in Fig. 2 (b).

If a virtual cathode forms, some of the electrons cannot reach the collector because they are bounced back by the virtual cathode. One way to reduce the influence of the space charge effect is to inject the plasma between the emitter and the collector, which is called ignition mode. In contrast, the interspace between the electrodes is in vacuum, which is called vacuum mode. If the system is changed from vacuum mode to ignition mode, positive ions in the plasma modify the virtual cathode. Therefore, the flowing current increases. Another method of reducing the influence of the space charge effect is to minimize the distance between the electrodes, because the flowing current varies as the inverse of $d^2$, as shown in the Child-Langmuir equation. In addition, field electron emission may be induced when the distance between the electrodes is sufficiently short [4].

2.2 Theoretical efficiency of a TEC

For simplicity, the following four assumptions are introduced to obtain the theoretical efficiency.

- All the released electrons from the emitter arrive at the collector.
- Because the collector is cold, the electron emission from the collector is negligibly small.
- Heat conduction and the voltage drop are neglected.
- The effect of electron emission cooling is neglected.

These assumptions are appropriate in the actual TEC system. When the emitter temperature is in the steady state, the energy balance is expressed as [3, 5]

$$Q = R + J_0 \phi_E,$$

(3)

where $Q$ is the heat flux flow in the emitter in W/m$^2$, and $J_0$ is the thermionic electron emission in A/m$^2$, shown in
Eq. (1). \( R \) is the thermal radiation from the emitter in W/m\(^2\) given by the Stefan-Boltzmann law as
\[
R = \sigma \varepsilon T_E^4,
\]
where \( \sigma \) is the Stefan-Boltzmann constant \([\sigma = 5.67 \times 10^{-8} \text{ W/(m}^2\text{K}^4)]\), and \( \varepsilon \) is the radiation factor, which is 0.5 – 0.9 for common metals.

On the other hand, if the output voltage is the difference in the work functions of the electrodes \( \Delta \phi = \phi_E - \phi_C \), the efficiency of TEC, \( \eta \), is expressed as
\[
\eta = \frac{J_0 \Delta \phi}{Q} = \frac{J_0 (\phi_E - \phi_C)}{R + \phi_E}.
\]

The efficiency of the TEC and the emitter temperature \( T_E \) are shown in Fig. 3, assuming that the emitter is made of tungsten \( (\phi_E = 4.5 \text{ eV}) \) and the collector is made of thoria-tungsten \( (\phi_C = 2.6 \text{ eV}) \). A radiation factor of 0.5 was used in this calculation. The efficiency increases with \( Q \) because thermionic electron emission is an exponential function of \( T_E \), and the radiation is proportional to \( T_E^4 \). If the heat flux from the divertor plasma, \( Q = 5 \text{ MW/m}^2 \), the electron temperature exceeds 3000 K even though the melting point of tungsten is \( \sim 3700 \text{ K} \).

3. Simulation

In this section, the TEC system is investigated by a two-dimensional PIC simulation code called the Berkeley code [6, 7]. PIC particles interact with fields defined at discrete locations in space (on a mesh, for example) according to an interpolation used to compute the forces on the particles [7–9]. The current and charge density source terms for Maxwell’s equations are generated by interpolation from the particle locations to the mesh. In the PIC simulation, the force between the particles is computed indirectly by resolving the Poisson equation without considering the direct Coulomb interaction between charged particles.

3.1 Vacuum mode

First, the TEC system in vacuum mode was investigated using the PIC simulation. Figure 4 shows a schematic of the simulation model, and Table 1 shows the parameters used in the calculation. Thermionic electron emission from the emitter was estimated from Eq. (1). The electron temperature, \( T_e \), was assumed to be 0.2 eV, which is equal to the emitter temperature, \( T_E \). Because the electrodes are much larger in size than the distance between them, a periodic boundary condition was used for the parallel direction of the electrodes. The effect of the external load was not considered in the calculation; this assumption is appropriate for investigating the motions of the charged particles between the electrodes.

Figure 5 (a) shows the output current density, \( J \), versus the emitter temperature, \( T_E \), obtained from the PIC simulation. The output current, \( J \), is compared to the Child-Langmuir law as the applied voltage, \( V \), was changed.
The vertical axis is the output current normalized to that obtained from the Child-Langmuir law, $J_{CL}$, and the horizontal axis represents the ratio of the applied voltage to $T_e$. In this simulation, $T_e$ was fixed, and $V$ was gradually changed from 0.01 V to 100 V. The output current is higher than that obtained by the Child-Langmuir law when $V/T_e$ is lower than 10. This is because the initial velocity of thermionic electrons increases with $T_e$, whereas the initial velocity of the released electrons is assumed to be zero in the Child-Langmuir equation. The Child-Langmuir law may be applicable when $V/T_e$ is comparably high, say $\geq 10$. However, because $V/T_e \sim 10$ under the present conditions, the Child-Langmuir law cannot be used for accurate evaluation. The operating conditions of the TEC system are in the region where $V/T_e$ is lower than 10 (if $T_E \sim 2000$ K and the emitter and the collector are made of tungsten and thoriated tungsten, respectively, the initial velocity $T_e \sim 0.2$ eV, and the potential difference between the electrodes is less than 2 V). Therefore, it can be said that Child-Langmuir equation may not be applicable, and precise numerical simulation is required under these conditions.

### 3.2 Ignition mode

In this study, “ignition mode” refers to a situation in which plasma is injected between the emitter and the collector to reduce the space charge effect. In the simulated ignition mode, ions are injected from the emitter and the collector as shown in Fig. 7. The ion temperature, $T_i$, is assumed to be 0.2 eV, which is equal to $T_e$ and $T_E$. The other parameters are shown in Table 1; the same parameters are used as for vacuum mode except for the ions injection. Figure 8 shows the output current density, $J$, versus the emitter temperature, $T_E$, obtained from the PIC simulation. In vacuum mode, the output current was not equal to the emission current when $T_E$ was higher than 2100 K. On the other hand, in ignition mode, ion injection reduces the space charge effect, and the output current increases. However, when the emitter temperature is higher than 2300 K, the space charge effect limits the output current. The output current varies with the ion injection current density, $I_i$, when $I_i = 500$ mA/m$^2$ and $T_E$.
Fig. 8 Emitter temperature dependence of the output current density obtained from the PIC simulation in ignition mode.

is higher than 2100 K. Note that when $T_E$ is high, say higher than 2300 K, the output current becomes significantly lower than that obtained from Eq. (1) even in the ignition mode.

Figure 9 (a) shows the ratio of the output current to the emission current, $J/J_0$, as a function of the ratio of the ion density to the electron density, $\langle n_i \rangle / \langle n_e \rangle$, for $T_E = 2300$ K. Here, the density is the number of particles divided by the size of the system (i.e., the mean density). The current ratio is 20% in vacuum mode ($\langle n_i \rangle / \langle n_e \rangle = 0$), because a considerable number of the released electrons are bounced back to the emitter. The output current increases with the ion density. Almost all the emitted electrons arrive at the collector when the space between the electrodes is filled with a quasi-neutral plasma.

Figure 9 (b) shows the potential profiles between the electrodes when $\langle n_i \rangle / \langle n_e \rangle = 0.4$ and 1.5. When $\langle n_i \rangle / \langle n_e \rangle = 0.4$, a virtual cathode is formed; thus, slow thermionic electrons returned to the emitter. On the other hand, when $\langle n_i \rangle / \langle n_e \rangle = 1.5$, the potential shape had a peak at $d = 0.4$ mm. Even if the velocities of all the initial electrons were zero, all the released electrons could reach the collector. Furthermore, Figs. 9 (c) and (d) are the density profiles between the electrodes when $\langle n_i \rangle / \langle n_e \rangle = 0.4$ and $\langle n_i \rangle / \langle n_e \rangle = 1.5$, respectively. In Fig. 9 (c), the ions and electrons densities are large near the emitter. In contrast, the densities are almost uniform between the electrodes in Fig. 9 (d).

If the TEC system operates in a fusion reactor, the effect of the magnetic field must be considered. Figure 10 shows the simulation model used to investigate this effect. The magnetic field strengths perpendicular and parallel to the electrodes are $B_x$ and $B_y$, respectively. In this simulation, $B_y$ was fixed at 0.1 T, and $B_x$ was gradually changed from 0.025 T to 0.6 T. $I_i$ was adjusted so that the space between the electrodes was filled with a quasi-neutral plasma for $B_x = B_y = 0$ T.

Figure 11 shows the ratio of the output current to the emission current and the ratio of the ion density to the elec-
**4. Experiments**

Verification experiments on the TEC system under fusion-relevant conditions were performed in the ACT, a heat load test device on the electron beam at the National Institute for Fusion Science that has been used for divertor plate tests.

A picture of the TEC test device is shown in Fig. 12(a). Materials that are durable under a high heat load are used for the electrodes. Both the emitter and the collector are made of 2% thoriated tungsten (work function, 2.6 eV; melting point, approximately 3500 K). Because the two electrodes are made of the same material, the potential difference is zero. To simulate a tungsten emitter in this experiment, the collector was biased by approximately +2 V with respect to the emitter. Thoriated tungsten was used instead of pure tungsten to increase the emission from the emitter by decreasing the work function. If the emitter is made of pure tungsten, its temperature should be raised to approximately 2300 K to obtain sufficient output current. We used thoriated tungsten for the emitter, and the emitter temperature was increased to approximately 1800 K. The electrodes are circular, 8 mm in diameter, and 0.5 mm thick. Dielectric parts were made of boron nitride (BN), which is durable under high heat flux conditions.

Figure 13 shows the ratio of the output current to the emission current as a function of the distance between the electrodes for $T_E = 2300$ K calculated with the PIC simulation. In this simulation, the emitter was assumed to be pure tungsten, and the collector was assumed to be thoriated tungsten. The simulation result shows that if the distance between the electrodes was $d \leq 100 \mu$m, the entire emission electron current became the output current.

To improve the space charge limit effect, we tried to minimize the distance between the emitter and the collector ($\leq 100 \mu$m) by using a BN spray. The process used to
Fig. 13 Simulated output current versus the distance between the electrodes.

Table 2 Experimental parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>mode</td>
<td>vacuum mode</td>
</tr>
<tr>
<td>work function of emitter $\phi_E$</td>
<td>2.6 eV</td>
</tr>
<tr>
<td>work function of collector $\phi_C$</td>
<td>2.6 eV</td>
</tr>
<tr>
<td>gap distance $d$</td>
<td>$\sim 60 \mu$m</td>
</tr>
<tr>
<td>square of electrodes $S$</td>
<td>$5 \times 10^{-5}$ m$^2$</td>
</tr>
<tr>
<td>bias between electrodes $V$</td>
<td>2 V</td>
</tr>
</tbody>
</table>

Form a short gap distance is shown in Fig. 12 (b). The central part of the electrode was masked with tape, and then a thin BN layer was formed by spraying. In this way, a system with a short gap ($d \approx 60 \mu$m) was constructed. Although the distance between the electrodes was evaluated with a scanning electron microscope, the distance seems to have an error of 10%. Table 2 shows the major experimental parameters. Figure 12 (c) shows a schematic of the experimental setup in the ACT. The emitter was heated by an electron gun (power is approximately 500 W), and the emitter temperature was increased gradually. Figure 14 shows the current density, $J$, versus the emitter temperature, $T_E$, measured with a radiation thermometer. Note that the radiation thermometer observed the target from a significantly oblique angle, and some of the BN might have been included in the spot, so the temperature seemed to be lower than the actual temperature of the electrode. To compensate for this effect, the temperature of the electrode in Fig. 14 was multiplied by a correction factor that is a function of the temperature. The factor $B$ was determined assuming that the output current density corresponds to the calculated electron emission from the emitter at low temperature according to the Richardson-Dushman equation. We defined the right-hand side as the correction factor $A$, which is a function of $T'$, and corrected the temperature using $T = AT'$. Hence, we obtain

$$\frac{T}{T'} = (1 - \frac{kT'}{h}\log B)^{-1}.$$ (8)

The factor $B$ was determined assuming that the output current density corresponds to the calculated electron emission from the emitter at low temperature according to the Richardson-Dushman equation. We defined the right-hand side as the correction factor $A$, which is a function of $T'$, and corrected the temperature using $T = AT'$. The experimental results agree well with the PIC simulation results. At high temperature, the output current did not saturate because the initial velocity of the high-velocity thermionic electrons increased with $T_E$. The bias voltage dropped with the current in the experiment, in contrast to the constant bias voltage in the numerical simulations. In this experiment, the TEC system effectively generated an electrical power of $10 \text{ kW/m}^2$ at $\sim 2000$ K. Given that the incident heat flux was $1 \text{ MW/m}^2$, the efficiency of this experiment was approximately 1%.

5. Conclusions

In this paper, the fundamental characteristics of a thermionic energy converter (TEC) under fusion-relevant
conditions were investigated numerically using a particle-in-cell (PIC) simulation code and experimentally using ACT, the heat load test device.

From the PIC simulation study, we evaluated the output current as the applied voltage was changed. We found that the Child-Langmuir law cannot be used for an accurate evaluation of the output current because of the effect of the initial velocity of the emitted electrons and a virtual cathode that formed in front of the emitter electrode. The TEC system was changed from vacuum mode to ignition mode, and the output current was measured. By injecting positive ions between the electrodes, that is, in ignition mode, we demonstrated that the virtual cathode was modified and the output current increased. We investigated the effect of the magnetic field by changing the angle of the incident magnetic field with respect to the electrodes. The output current decreased when the magnetic field was inclined because the oblique magnetic field corresponds to an effective increase in the distance between the electrodes. There might be feasible method of introducing plasma between the electrodes using a divertor plasma. This method requires further study. We conducted verification experiments on the TEC in vacuum mode in the ACT. The experimental results agreed well with the PIC simulation results, and the TEC system effectively generated 10 kW/m² of electrical power.

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