# Effects of heat transfer on characteristics of thermionic energy converter

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Effects of heat transfer on characteristics of thermionic energy converter

Weiwei Zhu, Cong Ji, Fan Gu

(School of energy and environment, Southeast University, Nanjing 210096, China)

Abstract: Photon Enhanced Thermionic Emission (PETE) is a new concept in solar energy conversion, combining thermal and photovoltaic carrier excitations with thermionic emission. A solar-power-driven thermionic energy converter operates by illuminating the solar light condensed by a large-scale Fresnel lens in order to convert heat energy into electrical energy. By enhancing the efficiency of converting solar radiation into the emitter internal energy, the output power and efficiency of the thermionic energy converter can be greatly improved. In this study, using numerical simulations, the effects of temperature of emitter and output characteristics on a thermionic energy converter were investigated. The results showed that the higher rate of the heating power represented the higher temperature of an emitter, as well as output current density, and efficiency. In addition, by reducing the diameter of a collector and thermal conductivity of insulation materials or increasing the diameter of emitter, the temperature of emitter, output current density, and efficiency could be notably improved. It is also worth mentioning that the main factor that affected the temperature of emitter in the process of heat transfer is heat conduction between solids. In conclusion, adequate illumination, reasonable size of collector and emitter, as well as appropriate insulation measurements could efficiently improve the output characteristics of thermionic energy converter.

Key word: Solar thermionic energy converter, numerical simulation, temperature of emitter, output characteristics of TEC, efficiency

E-mail: energy_seu@126.com
1 Introduction

Thermionic Energy Converter (TEC)\textsuperscript{1,2} is a vacuum device, converting directly the heat energy into the electrical energy. The TEC is such an appropriate tool for miniaturization, since it has no rotating or movable components. Compared with conventional energy conversion methods, the TEC avoids losing the mechanical energy in energy conversion process by improving the efficiency. It highly depends on the emission of hot electrons and the positive contact potential difference between the collector and emitter. This device converts the energy heating the emitter to a low voltage and high current output. This principle was presented in early 50s, in which it has been currently entered into the experimental and practical phases. Although there are several challenges and limitations in implementing a high efficient TEC, it is an excellent nominee for clean energy harvesting due to its noiselessness, scalability, reliability, and long lifetime characteristics. International conferences on thermionic devices have been held repeatedly. Moreover, the mentioned device has been reported annually on energy conversion engineering conferences since 1966. Over the years, several papers have represented the principle of it.\textsuperscript{3,4,5,6}

In recent years, the shortage of fossil energy resources and the relevant environmental pollutions are concerning different societies. In order to meet the growing energy demands and reduce the human’s dependency on the conventional energy resources, renewable and sustainable energy technologies are gaining more and more attention. Solar energy is widely used as a clean energy source. Solar TEC\textsuperscript{7,8,9,10} on the basis of high temperature Cs-Ba TEC was proposed. Solar TEC can use the entire wavelength of solar light as the energy source. Emitter heating is mainly done using a longer solar light wavelength, in which Ogino described in detail the heating of solar TEC emitters by illumination\textsuperscript{11}. In the solar energy TEC, the sunlight with the help of a large Fresnel lens aggregation irradiation generates a large number of excited cesium atoms. It is conducive to production of cesium ions and hot electrons through the inelastic collision. Experiments showed that the Solar TEC could generate electricity in the ignition mode\textsuperscript{12}, however, the output power is still small. Wei ZHENG, Akihisa OGINO and Masashi KANDO Zheng et al. have investigated the effects of illumination on the TEC characteristics\textsuperscript{13}. The results demonstrated that the illumination would accelerate the transition of TEC into the ignition mode and enhance the output current of TEC. The cathode of TEC, the emitter, emits high-energy electrons when severely heated, and these electrons are accepted by the collector to produce an electric current. The work function of emitter and receiver is regarded as one of the key issues that could affect the efficiency of TEC. Low power function materials have restricting the development of TEC. For many years, the scholars were looking for better materials to accelerate the development of TEC. Indeed, for TEC, the higher temperature of the emitter, generates the greater efficiency and output power. Lu Haolin studied the characteristics of tungsten nickel cylindrical TEC\textsuperscript{14}. Under the same light intensity, improving effectively the temperature of emitter results in enhancing the output power and efficiency of the solar TEC. Few studies have investigated the effect of heat transfer mode on TEC. Zhang reported the effect of near-field radiation on energy conversion.\textsuperscript{15}

In this paper, a TEC model has been numerically simulated. By changing the diameter of collector ($D_c$), diameter of emitter ($D_e$), heating power ($P$), and thermal conductivity ($k$) of insulating materials, the influence of heat transfer of collector, heat absorption of emitter, and the heat transfer of insulating materials on the output characteristics of TEC have been explored. It is such a significant approach for understanding and master the temperature distribution in the TEC by analyzing the complex heat transfer process. Numerical simulation using finite element analysis was carried out by COMSOL Multiphysics software in order to analyze the heat transfer in the TEC.
2 Mathematical and physical models and the relevant computations

2.1 Physical model

In this study, the TEC model has schematically been shown in Fig. 1. The model consisted of a small hole which was arranged at the left end of the shell of the model, and a thin ITO glass sheet was embedded into the model and could be used as heating window of the laser heater for emitter. The heat source is a continuous laser with wavelength of 1064 nm, Fellows Photonic, model specification: MSL-Chr1064. The length, diameter, the thickness of the side, as well as the remaining thickness of the model are 110, 60, 2, and 5 mm, respectively. In addition, the diameter of the heating window, the thickness of the corundum tube, the thickness of the carbon felt, and the distance from the emitter to the window are 5, 1.5, 3, and 55 mm, respectively. In order to investigate the influence of the heat absorption in emitter on the TEC characteristics, the heating power varied from 9 to 15 W were calculated accordingly. The emitter is a thorium tungsten electrode. It should be mentioned that, herein, the effect of heat transfer in the collector and emitter on the TEC characteristics with the diameters of 1 to 1.6 mm, and 3 to 6 mm were computed as well. Heat insulating materials are filled between the shell and the emitter and the collector. By investigating the effect of heat transfer in the thermal insulation materials on the TEC characteristics, the thermal conductivity coefficient of the insulation material was in the range of 0.03 to 0.06 W/(m·K). Fig.2 shows a section of the device, indicating the structure.

2.2 Calculation of temperature field

Using Heat Transfer Module, the physical model is a surface-to-surface radiation, and the governing equations are discretized by finite difference method, applying smoothing to the boundary fluxes. The heat transfer process of the device basically involves convection heat transfer between outer wall surface and atmosphere, solid heat conduction in the device, and radiation heat transfer between inner walls.

2.2.1 Convective heat transfer between outer wall and the atmosphere

\[
q_0 = h \times (T_{\text{ext}} - T)
\]
where \( q_0 \) (W/m\(^2\)) is the convective heat transfer heat. \( h \) (W/(m\(^2\)·K)) is the convective heat transfer coefficient, \( T_{\text{ext}} \) (K) represents the external ambient temperature and \( T \) (K) denotes the surface temperature of device. The numerical value of the convective heat transfer coefficient is closely related to the physical properties of the fluid, the shape and position of the heat transfer surface, the temperature difference between surface and fluid, and flow velocity. The larger value of the flow velocity near the surface contains the larger value of the convective heat transfer coefficient. For the natural convection of air, the approximation order of convective heat transfer coefficient is 5~25 W/(m\(^2\)·K) .

2.2.2 Solid conduction

In the proposed model, the thermal conductivity of the heat preservation materials and other parts were calculated by the following equation

\[
\rho C_p \frac{\partial T}{\partial t} + \rho C_p u \times \nabla T + \nabla \times q = Q + Q_{\text{rad}}
\]  
(2)

\[
q = -k \nabla T
\]  
(3)

where \( \rho \) (kg/m\(^3\)) is density of solid, \( C_p \) (J/(kg·K)) represents the solid heat capacity at constant pressure and \( k \) (W/(m·K)) is thermal conductivity of solid materials. The thermal conductivity of different materials is non-identical, while the thermal conductivity of a certain substance is related to its structure, density, humidity, temperature, pressure, and other parameters. \( u \) (m/s) represents the velocity field, \( Q \) (W/m\(^3\)) is a heat source (or sink) and \( Q_{\text{rad}} \) denotes Thermoelastic damping

\[
Q_{\text{rad}} = -\alpha T \left( \frac{\partial S}{\partial t} \right)^{-1}
\]  
(4)

where \( S \) is the second Piola-Kirchhoff tensor and \( \alpha \) is the coefficient of thermal expansion.

2.2.3 Radiative heat transfer

The net inward radiative heat flux, \( q \) is given by difference between the irradiation and the radiosity:

\[
q = G - J_0
\]  
(5)

For the interior of the device, the radiation heat transfer exists among different surfaces. For a solid surface, the radiation energy budget is correlated with its own emission and absorption of external radiation. The energy budget of a surface is determined by Eq. (5).

The radiosity \( J_0 \) is sum of the reflected and emitted radiations. For diffuse-gray surfaces, \( J_0 \) is defined by:

\[
J_0 = (1 - \varepsilon) G + \varepsilon e_s(T)
\]  
(6)

where \( \varepsilon \) denotes surface emissivity, a dimensionless parameter in the range of \( 0 \leq \varepsilon \leq 1 \). The diffuse-gray surface hypothesis is correlated with surfaces where \( \varepsilon \) is independent of the radiation wavelength.

\[
e_s(T) \text{ (W/m}^2\text{)} \text{ represents blackbody hemispherical total emissive power}
\]

\[
e_s(T) = n^2 \sigma T^4
\]  
(7)

where \( n \) represents a refractive index, and \( \sigma \) is the Stefan-Boltzmann constant equal to \( 5.67 \times 10^{-8} \) W/(m\(^2\)·K\(^4\)) .

\( G \) (W/m\(^2\)) is the incident radiation, and is defined by

\[
G = \int_{4\pi} I(\Omega) d\Omega
\]  
(8)

where \( I(\Omega) \) (W/(m\(^2\)·sr)) denotes the radiative intensity at a given position following the \( \Omega \) direction, satisfying the radiative transfer equation

\[
\Omega \times \nabla I(\Omega) = \kappa I_s(T) - \beta I(\Omega) + \sigma \int_{4\pi} I(\Omega') \Omega \cdot \Omega' d\Omega'
\]  
(9)
where \( \kappa \) is absorption coefficient, \( \beta \) is extinction coefficient, \( \sigma \) denotes a scattering coefficient and \( \Phi(\Omega', \Omega) \) is scattering phase function.

\[
I_b(T) \text{ (W/(m}^2\text{-sr))} \quad \text{represents the blackbody radiative intensity which can be calculated by}
\]
\[
I_b(T) = \frac{n_r^2 \sigma T^4}{\pi}
\]  

(10)

where \( n_r \) is an refractive index.

Additionally, the radiation calculation of the heating window is specially dealt with.

Fig. 3 shows the spectral radiation force curve \( E(\lambda) \) of emitter in the temperatures of 1400, 1600, 1800, and 2000 °K, and reflectivity (\( R \)) of the ITO thin film whose thickness and electron concentration are equal to 0.41 \( \mu \text{m} \) and is \( 8 \times 10^{20} \text{cm}^3 \), respectively. For the device, when the emitter is heated to a higher temperature, a great deal of thermal radiation is produced. As shown in Fig. 3, when the emitter is heated to 2000 °K, the energy radiated from the emitter is concentrated in the range of wavelengths which is larger than 1 \( \mu \text{m} \). Moreover, the ITO film in the infrared range, which is close to positive reflection, could efficiently decrease heat dissipation from the heating window.

In the computation process, the spectral radiation force of the emitter is obtained by

\[
E(\lambda) = \frac{c_1 \lambda^{-5}}{e^{c_2/\lambda} - 1}
\]

(11)

where \( E(\lambda) \) (W/m\(^3\)) is the blackbody spectrum radiation force, \( \lambda \) (m) represents the wavelength, and \( c_1 \) denotes the first radiation constant in which its value is \( 3.7419 \times 10^{16} \text{ W/m}^2 \). \( c_2 \) is second radiation constant, equal to \( 1.4388 \times 10^2 \text{ m·K} \).

The energy that is reflected back to the heating window at a specific wavelength (See Fig. 3) is

\[
E_b(\lambda) = E(\lambda)R
\]

(12)

The total reflection is

\[
E_f = \int E_b(\lambda) \, d(\lambda)
\]

(13)

The energy of reflection can continually be used in order to heat the emitter. The energy dissipated by the heating window can be computed

\[
E_{loss} = \int E(\lambda)(1 - R)d(\lambda)
\]

(14)

2.3 Calculating the output current density and theoretical efficiency of TEC

The current density \( J_c \) from cathode to anode can be expressed as Richardson-Dushman equation

\[
J_c = A T_c^2 \exp\left(-\frac{\phi_c}{k_B T_c}\right)
\]

(15)

where \( A \) (A/cm\(^2\)·K\(^2\)) represents Richardson constant, \( \phi_c \) denotes work function of the cathode, \( T_c \) (K) is absolute temperature of the cathode, \( e \) (coulomb) represents electronic charge and \( k_B \) (joule/K) is Boltzmann constant.

Similarly, the current density \( J_a \) from the anode to the cathode can be expressed as
\[ J_a = AT_a^2 \exp\left(-\frac{e\phi_a}{k_BT_a}\right) \]  
\[(16)\]

where \( \phi_a \) is work function of the anode, and \( T_a \) (K) denotes absolute temperature of anode. Herein, the impact of \( J_a \) was ignored.

The output current density of TEC \( J \) is

\[ J = J_c - J_a \]  
\[(17)\]

Theoretical efficiency \( \eta \) considering all the energy losses of cathode can be computed using the following equation\(^\text{17}\)

\[ \eta = \frac{J_c(\phi_c - \phi_a - V_w)}{R_0 + H_w + J_c(\phi_c + 2k_BT_c/e)} \]  
\[(18)\]

where \( R_0 \) (W/cm\(^2\)) is net radiation from cathode to anode, \( H_w \) (W/cm\(^2\)) is heat transferred to cathode lead wire per unit area of cathode. In addition, \( V_w \) (V) is voltage dropped along cathode lead wire, and \( H_w \) and \( V_w \) are relatively minor, while their effects have been ignored.

### 2.4 Boundary condition

The ambient temperature is around 293.15 °K. Natural convection heat transfer coefficient is 20 W/(m\(^2\)·K), the emitter heating surface emissivity is 0.9, the other electrode surface emissivity is equal to 0.7, and the other surface emissivity is 0.3. The processing of the heating window has been described in detail. When calculating the output current density and theoretical efficiency, \( V_c \) and \( V_a \) are 3 and 2 V, respectively.

### 3 Results and Discussion

#### 3.1 Output characteristics

According to Figs. 5 and 6, for the TEC model, when temperature of the emitter reached 1600 °K, the output current density initially increased, and amplified after 1800 °K. In the beginning, the efficiency of the TEC was very small, and it commenced to increase after reaching the temperature 1600 °K. This temperature can be regarded as initial temperature of the TEC, while the efficiency tends to be constant when the temperature reaches 2100 °K.

---

\[ J_a = AT_a^2 \exp\left(-\frac{e\phi_a}{k_BT_a}\right) \]  
\[(16)\]

was spread out from the emitter, and the temperature gradient near the collector is large; consequently, the two meshes are interconnected.
3.2 Investigating the effects of heat transfer on a collector

Fig. 7 illustrates the temperature field distribution of the TEC when the diameter of a collector is changed. As shown in Fig. 7, the larger diameter of a collector contains the lower temperature of the emitter. For TEC, the lower temperature of the emitter represents the lower conversion efficiency, as shown in Fig. 8. Fig. 8 depicts a relationships between the output current density and the efficiency associated with diameter. As shown in Fig. 8, once the diameter has increased, the output current density and efficiency have been decreased. Fig. 9 shows the variation of the surface radiation and the total heat flux with the increasing the diameter. It can be clearly seen that the collector surface radiation and the total heat flux was increased with increasing the diameter. The change of surface radiation is small, but the total heat flux is considerable. This demonstrates that the heat transfer of a collector is generally changes when the diameter varies, and accordingly, the temperature field distribution of the TEC changes. With increasing the diameter of a receiver, the temperature of an emitter diminishes. This is often attributed to the increasing the energy dissipation by solid heat conduction, leading to the reduction of efficiency. Fig. 10 displays the relationships between upper surface radiation, total radiation, and thermal conductivity of an emitter associated with diameter. As shown in Fig. 10, once diameter increases, the thermal conductivity enhances as well, while the total radiation decreases. This represents that the main parameter affecting the temperature of emitter and the efficiency is heat conduction between the solid. Although the total radiation is reduced, the radiation on the emitter surface is increased, accordingly, the radiation received by a collector is increased as well.
3.2 Effect of absorption heat of emitter

Fig. 11 illustrates the temperature field distribution of TEC under different heating values. As shown in Fig. 11, the higher power contains the higher temperature of the emitter. As shown in Fig. 12, the greater power represents higher output current density and efficiency. The increasing trend of output current density is fully clear, while the increasing trend of efficiency is slower. Hence, although increasing the heating power can improve efficiency, however, it cannot be infinitely enhanced. When the heating power reaches a certain value, its variation has a trivial effect on the output efficiency of TEC. As shown in Fig. 13, with amplifying the heating power, the heat conduction between emitter and device as well as the radiation of emitter surface are increased. However, the ratio between the two has been reduced from 4.02 to 2.08, demonstrating that with increasing the heating power, the effect of the heat conduction between the emitter and the device is getting smaller and smaller, while the effect of radiation heat transfer is becoming more significant. However, thermal conductivity is still regarded as the main parameter affecting the efficiency.
3.3 Effects of heat transfer on the thermal insulation materials

Fig. 14 shows the temperature field distribution of the TEC with different thermal insulation materials. As shown in Fig. 14, the larger value of thermal conductivity contains lower temperature of the emitter. Fig. 15 depicts the relationships between the output current density and the efficiency with thermal conductivity. As shown in Fig. 15, once the thermal conductivity of thermal insulation material increases, the output current density and efficiency decreases. Fig.
16 displays the variation of heat conduction and radiation of an emitter and heat flux of insulation material with increasing the thermal conductivity. As shown in Fig. 16, the greater value of the thermal conductivity represents higher heat flow through the insulation material, showing that the dissipated energy. With enhancing the thermal conductivity, in general, the thermal conductivity of an emitter increases, while the amount of radiation decreases, indicating that the main reason for reducing the temperature of an emitter and efficiency is the heat conduction between solid.

![Fig.14 Temperature field distribution under thermal insulation materials with different coefficients of thermal conductivity](image)

![Fig.15 Relationships between output current density and efficiency associated with thermal conductivity](image)

![Fig.16 Relationships between conduction, radiation of emitter and heat flux of thermal insulation materials associated with thermal conductivity](image)

3.4 Effects of diameter of an emitter

Fig. 17 illustrates the temperature field distribution of TEC once the diameter of emitter
changes. As illustrated in Fig. 17, the larger diameter of a collector represents lower temperature of the emitter. As depicted in Fig. 18, the smaller diameter contains lower output current density and efficiency. With reducing the diameter of an emitter, output current density increases rapidly, while the efficiency tends to be constant. Therefore, although decreasing the diameter of an emitter would enhance the efficiency, however, it could not be infinitely improved. When the diameter reaches a certain value, its change has negligible influence on the output efficiency of the TEC. As shown in Fig. 19, with enhancing the value of diameter, the heat conduction between emitter and device decreases, while the radiation of emitter surface increases. It is worth mentioning that the ratio between the two has been reduced from 5.82 to 1.53, demonstrating that with the increasing the diameter of a collector, the influence of the heat conduction between the emitter and the device is becoming smaller. In addition, the effect of radiation heat transfer is becoming more important, while the thermal conductivity has still remained as the main factor affecting the efficiency.

![Fig.17 Temperature field distribution under different diameters of emitter](image)

![Fig.18 Relationships between output current density and efficiency associated with diameter of an emitter](image)

![Fig.19 Relationships between conduction, radiation of emitter and ratio between the two with emitter diameter](image)
4 Conclusions

The Solar TEC could generate high power output in ignition mode, while the high power required for heating the emitter was gathered by a large Fresnel lens. For Solar TEC, there are external and internal parameters affecting the efficiency. The following conclusions have been drawn from this study:

1. The temperature of 1600 °K can be taken into account as a critical temperature of the TEC. After $T_c$ reaching 1600 °K, the output current density and efficiency of the TEC were clearly increased.

2. With increasing the diameter of a collector, the heat conduction of a collector often enhanced, and then, the heat conduction between the emitter and the device increased as well. By reducing the temperature of an emitter, the output current density and efficiency of TEC eventually decreased.

3. With increasing the heating power, the heat absorption of an emitter simultaneously increased. The heat conduction and radiation heat transfer between the emitter and the device have been increased as well. Finally, once the temperature of an emitter rose, the output current density and efficiency of the TEC increased.

4. When the thermal conductivity of thermal insulation material increased, the dissipating energy increased as well. Once the heat conduction between the emitter and the device enhanced, the temperature of an emitter reduced, and the output current density and efficiency of the TEC decreased as well.

5. When the diameter of an emitter increased, conduction of an emitter is reduced, while the radiation increased. With decreasing the temperature of an emitter, the output current density and efficiency of the TEC finally decreased.

Therefore, the Solar TEC should be installed in sunny places, and ensure that the transmitter can receive adequate radiation. Under the same solar illumination conditions, the improvement of its characteristics solely depends on the device. On the one hand, the size of collector and emitter should be controlled to improve the characteristics of the TEC when not affecting the function. On the other hand, good insulation measurements should be undertaken to reduce heat loss of the TEC, through increasing its output power and efficiency.

References

