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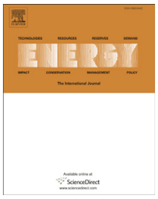

Performance evaluation and parametric optimum design of an updated thermionic-thermoelectric generator hybrid system

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ABSTRACT

An updated model of the hybrid system consisting of a vacuum TIG (thermionic generator) and a multi-couple TEG (thermoelectric generator) is proposed, in which the main internal and external irreversible losses of the system are considered and the temperatures of the electrode plates of the TIG and the cold side of the TEG are determined by energy balance equations rather than some specified parameters. Analytical expressions for the power output and efficiency of the TIG, TEG, and hybrid system are derived. The effects of the voltage output and work functions of the TIG and the electric current of the TEG on the power output and efficiency are discussed. The maximum power output and efficiency of the hybrid system are numerically calculated. The optimally operating regions of main parameters are determined.

1. Introduction

The increasing energy consumption, accompanied by environmental contaminations and climate changes, is driving the researches in efficient and reliable energy conversion devices. In recent years, many methods have been developed and applied to the performance analysis of heat transfer processes and the optimal design of thermal systems [1–3]. TIGs (Thermionic generators) and TEGs (thermoelectric generators) are unique heat engines using electrons as the working substance without mechanically moving parts [4–7]. The TIG is composed of a cathode absorbing heat from the heat source, an anode releasing the waste heat to the heat sink, and an external load that allows the electrons to move through. The electric current is based on the electron emission from the electrodes, where high energy electrons flow from the hot electrode to the cold electrode against the electrical potential difference [8]. During this process, the space charge accumulation could affect the conversion efficiency and has been considered by many articles. Smith presented a theory to model the space charge effects during the electronic transmission process between the two electrodes of the TIG employing a negative electron affinity emitter material [9]. In the photo-enhanced thermionic energy converter, Tsuyohito added cesium into the gaps to generate charge-neutralizing plasma using continuous laser, by which the space charge effects are possibly overcome [10]. As an alternative to use plasma, one possible solution to mitigate the space charge effects is to use nanometer vacuum gap in the TIG [11]. Wang et al. proposed a vacuum gap thermionic generator model considering the internal and external irreversible heat losses, where the influences of the work functions of electrodes and voltage output on the performance of the TIG were discussed [7]. Because thermionic energy converters are limited to work at high temperatures, the hybrid systems composed of the TIG [10–12] and other devices [13–15] operating at low temperatures are also an attractive research topic.

The TEG is a promising device to combine with the TIG which has advantages to recycle the waste heat to generate electrical energy [13–18]. In a thermoelectric module, p- and n-type semiconductor thermoelectric materials are connected electrically in series and thermally in parallel [19–22]. The motion of electrons in the TEG is quasi-equilibrium and diffusive, while the motion of electrons in the TIG is ballistic [23]. A number of thermoelectric models have been proposed to analyze the performance and heat

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transfer of the TEG [24–27]. Chen et al. have revealed the influences of external irreversiblities and operative conditions on a multi-couple thermoelectric generator [24]. Lee developed the optimal design of thermoelectric devices in connection with heat sources using dimensional analysis [25]. Kim proposed an analytic model to measure the internal temperature difference of a TEG [26]. Wang et al. considered a general model with the coupling of the electric potential field and temperature field [27].

A hybrid system consisting of the TIG and TEG was predicted to be highly efficient by Xuan and Li [28]. Their prediction was based on a model of combined thermionic-thermoelectric generator. To simplify the model, they specified the operating temperatures of the TIG and TEG and ignored the irreversible losses between the system and the heat reservoirs. The present work presents an updated model that makes no such simplification and thus is well-suited to optimize the whole performance and obtain the choice criteria of key parameters of the hybrid system. The temperatures of the cathode and anode in the TIG and the cold side of the TEG are not specified, and consequently, they must be determined by the energy balance equations. On the other hand, a general model of the TEG is adopted so that the influence of the Thomson effect is included. Thus, the effects of the work functions of the TIG and the electric current of the TEG on the performance of two subsystems and hybrid system can be directly discussed. The key parameters of the hybrid system are optimized, so that some useful results for the optimum design of practical hybrid systems are obtained.

2. An irreversible thermionic-thermoelectric generator hybrid system

Fig. 1 shows the schematic diagram of a thermionic-thermoelectric generator hybrid system operating between two heat reservoirs. Q_H is the heat flow absorbed from the heat source at temperature T_H to the cathode of the TIG. Q_C is the heat flow released from the cold side of the TEG to the heat sink at temperature T_C. The thermionic generator is composed of two metal plates with a vacuum gap in the middle. The thermoelectric generator consisting of multi-couple semiconductor elements connected electrically in series and thermally in parallel is thermally connected to the anode of the TIG.

For the sake of generality, the heat transfer between the system and two heat reservoirs at temperatures T_H and T_C is assumed to obey, respectively, radiation law and Newton's law. The heat flows can be expressed as

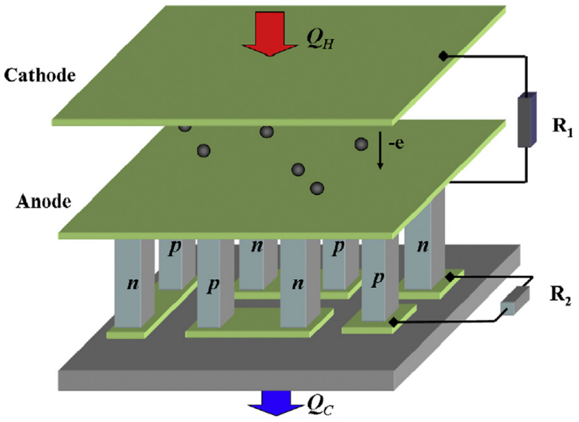

Fig. 1. The schematic diagram of a thermionic-thermoelectric generator hybrid system.

$$Q_H = F_1 \varepsilon_1 \sigma \left(T_H^4 - T_1^4\right) \tag{1}$$

and

$$Q_C = F_3 U_3 (T_3 - T_C), \tag{2}$$

where F_1 is the effective heat exchange area between the heat source and the cathode, ε_1 is the thermal emissivity, σ is the Stefan–Boltzmann constant, T_1 and T_3 are, respectively, the temperatures of the cathode in the TIG and the cold side in the TEG, F_3 is the effective heat exchange area between the heat sink and the cold side of the TEG, and U_3 is the heat-transfer coefficient.

2.1. The output power and efficiency of a TIG

When the system works under normally operating condition, the cathode of the TIG absorbs the heat from the hot reservoir. The electrons in the cathode are rapidly thermalized, emitted out of the cathode surface, and collected by the anode. The voltage output of the TIG depends on the difference of two work functions of the cathode and anode. The electrical current densities from the cathode and anode are given by the Richardson equation, i.e. [8,11],

$$J_{TI}^c = A_0 T_1^2 \exp\left(-\frac{\Phi_c}{k_B T_1}\right) = A_0 T_1^2 \exp\left(-\frac{\Phi_a + qV}{k_B T_1}\right) \tag{3}$$

and

$$J_{TI}^a = A_0 T_2^2 \exp\left(-\frac{\Phi_a}{k_B T_2}\right), \tag{4}$$

where Φ_c and Φ_a are the work functions of the cathode and anode, $V = (\Phi_c - \Phi_a)/q$ is the voltage output of the TIG, A_0 is the Richardson–Dushmann constant, T_2 is the temperature of the anode, k_B is the Stefan–Boltzmann constant, and q is the absolute value of the electron charge. By using Eqs. (3) and (4), the net electrical current density J_{TI} can be written as

$$J_{TI} = J_{TI}^c - J_{TI}^a = A_0 T_1^2 \exp\left(-\frac{\Phi_a + qV}{k_B T_1}\right) - A_0 T_2^2 \exp\left(-\frac{\Phi_a}{k_B T_2}\right). \tag{5}$$

For the sake of simplicity, it is reasonable to assume that the two plates of the TIG have the same area F_1 [7,9–12,28]. The rates of heat flow through the cathode and anode are, respectively, given by

$$Q_1 = F_1 \left[\left(V + \frac{\Phi_a + 2k_B T_1}{q}\right) J_{TI}^c - \left(V + \frac{\Phi_a + 2k_B T_2}{q}\right) J_{TI}^a + \varepsilon_0 \sigma \left(T_1^4 - T_2^4\right)\right] \tag{6}$$

and

$$Q_2 = F_1 \left[\frac{\Phi_a + 2k_B T_1}{q} J_{TI}^c - \frac{\Phi_a + 2k_B T_2}{q} J_{TI}^a + \varepsilon_0 \sigma \left(T_1^4 - T_2^4\right)\right], \tag{7}$$

where ε_0 is the thermal emissivity of the inner surfaces of the cathode and anode. According to Eqs. (5)–(7), the power output and efficiency of the TIG can be expressed as

$$P_{TI} = F_1 J_{TI} V = F_1 A_0 V \left[T_1^2 \exp\left(-\frac{\Phi_a + qV}{k_B T_1}\right) - T_2^2 \exp\left(-\frac{\Phi_a}{k_B T_2}\right)\right] \tag{8}$$

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