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**Theoretical Investigation of a Thermoelectric Generator for Harvesting Waste Heat from Fuel Cell**

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Abstract

Fuel cell not only generates electricity but also releases a great deal of waste heat. If the waste heat can be harvested by hybridizing thermal devices, the overall energy conversion efficiency will be boosted. In this study, a thermoelectric generator is employed to recover the waste heat from fuel cell. Based on Fourier’s law, Seebeck effect, Peltier effect and Thomson effect, the energetic performance of thermoelectric generator (TEG) is evaluated. Mathematical simulation model is developed by Matlab software and the results show that the maximum power output and corresponding efficiency of TEG with Thomson effect are, respectively, 0.57 W and 2.71%, which are much lower than that of TEG without Thomson effect. Furthermore, the influences of phase change material, the heat source temperature, total number of thermoelectric elements and the cross-sectional area of semiconductor legs are analyzed. The derived results may provide new insights for understanding the energetic performances of such an actual system.

**Keywords:** Thermoelectric generator, Waste heat recovery, Phase change material, Thomson effect, Parametric analysis

# **Introduction**

Owing to the limited fossil fuel sources and the comprehensive impacts of environmental pollution, alternative energy technology development has become a global consensus [1]. Compared with wind and solar power systems, fuel cell power generation system is more feasible and applicable [2]. Generally, the electrical efficiency of fuel cell in continuous operation is about 40% - 60% [2], and nearly half of the chemical energy is dissipated in the form of heat. For example, previous studies [3, 4] show that the heat waste rate of fuel cell can be increased from 0 to above 40 W with the increase of electrical current when the working temperature is between 430 K and 470 K. Thus, waste heat recovery is an important way to improve the thermal efficiency of fuel cell, which has become the focus of attention.

Thermoelectric generator (TEG), as a power generation device, is widely utilized in recovering waste heat from fuel cell because of its environmental protection, reliability and scalability [5]. However, the amount of heat recovered is very limited, generally less than 5%. This is to a certain extent restricted by thermoelectric materials. Despite the challenges, it is possible to harvest large amounts of waste heat from fuel cell by using thermoelectric device, especially with the development of material research and the application of heat transfer technology. Bell [6] put forward two important ways, which will bring to the further application for thermoelectric device. One is to enhance the inherent efficiency of thermoelectric material. From the perspective of current development and investigation on new thermoelectric materials, large amounts of thermoelectric researches focus on improving the conversion efficiency of thermoelectric materials. New technologies in semiconductor physics and solid state physics [7], as well as nanotechnology [8] are used to explore this field. Alternative way is about improving the exiting use of TEG. Besides to the investigation on thermoelectric materials, reasonable thermal management and design of TEG are also significant for improving power generation performance [9]. The critical factor is the efficient utilization of heat source. For example, Wu et al. [10] presented energetic analyses on a combined system which consists of a phosphoric acid fuel cell and a thermoelectric device. Their study revealed that both of the energy efficiency and power density were effectively increased over 2.0% compared with the single phosphoric acid fuel cell. Yang et al. [11] utilized a TEG to recover the exhausted heat from alkaline fuel cell. It was found that the power density of the hybrid system could be up to 23%. Sark [12] simulated a hybrid system composed of a TEG and a photovoltaic module, and the results showed that the solar efficiency was improved by 8-23%. It is worth noting that the TEG models of these systems in [10-12] do not consider Thomson effect, which refers to the generated reversible heat when electrical current passes through a conductive material which is affected by temperature gradient. However, if the Seebeck coefficient is considered as temperature dependent and the temperature difference between two sides of TEG is large, Thomson effect must be considered [13, 14]. In addition, the connection and heat transfer between fuel cell and TEG are often simplified, and equaling the working temperature of fuel cell to the hot side temperature of TEG, which is inconsistent with the actual situation [3, 15]. Furthermore, low convective heat transfer coefficient is one of the important factors that restrict the performance of TEG with waste heat as heat source [16]. Because of the large phase change heat transfer coefficient, phase change material can be used to strengthen the heat transfer between the heat source and TEG [16]. Presently there is no literature on energy analysis on TEG that considers Thomson effect and heat transfer between fuel cell and TEG.

In order to fill this research gap, a TEG considering Thomson effect is proposed to harvest the exhaust heat from fuel cell which operating temperature can be in the region of 430 K - 470 K. Meanwhile, a heat exchanger filled with phase change material will be used to connect the fuel cell and TEG. The effects of Thomson effect, phase change material, heat source temperature, thermoelectric element number and the cross-sectional area of semiconductor legs on the TEG performance will be revealed to evaluate the effectiveness and feasibility of using the TEG as the waste heat recovering technology for fuel cell.

# **Methodology**

## 2.1 Physical Model

Fig. 1 (a) shows the heat flow diagram of fuel cell-phase change material-TEG hybrid system, the waste heat of fuel cell is transferred to the phase change material in the heat exchanger, and then shifted to TEG to generate electric energy based on the Seebeck principle. The waste heat from TEG is released to the environment.  and  are the hot side temperature and cold side temperature of TEG respectively,  and  are the heat source temperature and environment temperature respectively.  is the heat-transfer rate from the fuel cell to the phase change material,  stands for the heat transfer rate from the phase change material to the hot junction of TEG; and  is the heat-transfer rate from the cold side of TEG to the ambient environment;  is the power output produced by TEG.

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Fig. 1. (a) The heat flow diagram among subsystems and (b) the schematic diagram of the fuel cell-phase change material-TEG system.

The assumptions are used for the following analyses:

* TEG is operated in a steady state [17, 18];
* The thermal contact resistance between junctions in TEG is negligible [19];
* The cold side temperature of TEG equals to the ambient temperature [20];
* The electrical resistance and thermal conductance of conducting metals in TEG are ignored [18];
* The heat loss in the heat exchanger is neglected;
* The electrical contact resistance between junctions in TEG is regarded to be 10% of the total resistance of the thermoelectric elements (TEEs) [19].

## 2.2 Mathematical Model

## As shown in Fig. 1 (b), TEG consists of many TEEs, which are linked thermally in parallel and electrically in series by using metal strips. The total number of TEEs is , and each TEE has a P-type semiconductor leg, an N-type semiconductor leg, two ceramic plates and three metal connectors [21]. The TEEs are manufactured from Bismuth Telluride (Bi2Te3) in this study, and the Seebeck coefficient , thermal conductivity and electrical resistivity are, respectively, given by Eqs. (1), (2) and (3) [22].

 (1)

 (2)

and

 (3)

where the subscript  stands for P-type and the subscript stand for N-type; . The Thomson coefficient  is defined as Eq. (4) [23].

 (4)

Since Seebeck coefficient is related to temperature, Thomson effect can not be ignored [24]. According to Eqs. (1) and (4),  can be rewritten as Eq. (5) [25].

 (5)

In consideration of the Peltier effect, Seebeck effect and Thomson effect, the energy balance equations at hot and cold side of TEG are, respectively, described as Eqs. (6) and (7) [26].

 (6)

and

 (7)

where  is the electrical current of TEG. The electrical resistance  and thermal conductance  of a TEE are, respectively, given by Eqs. (8) and (9) [27].

 (8)

and

 (9)

where  and  are, respectively, the length and cross-sectional area of semiconductor legs; ; ;  and  stand for the electrical resistance and electrical conductance of a semiconductor leg respectively;  and  are the electrical resistance and electrical conductance between conducting metals and junctions respectively;  and  are, respectively, the electrical resistance and electrical conductance of conducting metals.

The power output of TEG  can be given by Eq. (10) [28].

 (10)

Substituting Eqs. (6) and (7) into Eq. (10),  can be further rewritten as Eq. (11).

 (11)

The energy efficiency of TEG  can be described by Eq. (12) [15].

 (12)

As the low convection heat transfer coefficient between heat source and TEG is one of the important factors restricting TEG performance [16]. In order to establish a more practical model for a waste heat-driven TEG, the connection and convection heat transfer between heat source and TEG is also considered in this study. As phase change heat transfer has a huge coefficientfor forced convection [16], so phase change material which has a phase change temperature slightly lower than heat source temperature is employed in this study to strengthen the heat transfer between the heat source and TEG. Phase change fluid absorbs the heat of the fuel cell in the heat exchanger and then boils, releases the heat to the hot side of TEG and condenses into liquid. The energy balance between fuel cell and TEG is given by Eq. (13).

 (13)

where  is the cross-sectional area of heat exchanger;  is the phase change convection heat transfer coefficient of exhaust, which is assumed to be 2000 W m-2 K-1 in this study.

Table 1: Parameters used in the modeling.

|  |  |
| --- | --- |
| Parameter | Value |
| Cross-sectional area of heat exchanger  (m2) | 0.04 |
| Cross**-**sectional area of semiconductor legs  (m2) | [17] |
| Length of semiconductor legs,  (m) |  |
| Number of TEE pairs, | 20 [20] |
| Temperature of environment,  (K) | 300 |
| Exhausted gas temperature,  (K) | 450 |
| Phase change heat transfer coefficient of exhaust,  (W m-2 K-1) | 2000 |
| Normal heat transfer coefficient of heat exchanger,  (W m-2 K-1) | 20 |

Considering the heat loss between hot and cold junctions, TEG can only work when the inequality (14) is valid.

 (14)

where  is the minimum input heat rate that the TEG starts to work. When , the mathematical relationship between input heat rate  and TEG electric current  can be obtained by equalizing Eqs. (6) and (13).

 (15)

Taking Eqs. (11) and the condition of into account, the maximum input heat transfer rate, , can be calculated, from which TEG is a heating resistance, not an electric power generator. As a result, TEG can only work in the interval of inequality (16).

 (16)

Based on Eqs. (11) and (12), the power output  and energy efficiency  of TEG can be, respectively, given by Eq. (17).

 (17)

 (18)

The power output is selected as the optimum criterion, and the optimum working region of  for TEG is inequality (19).

 (19)

where  is the corresponding value when  reaches it maximum value .

Correspondingly, the optimum regions for and  are, respectively, determined by inequality (20) and (21).

 (20)

and

 (21)

where  and  are the corresponding values when ;  and  are the corresponding values when . , , (i.e., ),  and  are five key parameters to characterize the property of TEG.

1. **Results and discussion**

Q VS I P ThomsonI VS YITA Thomson

Fig. 2. Electrical current and power output varying with input heat rate with or without Thomson effect, where  is the maximum power output of TEG;  and  are, respectively, the input heat rate and electrical current of TEG at ,  and  are, respectively, lower and higher bound input heat rate that enables TEG to work.

Fig. 3. Electrical current varying with efficiency with or without Thomson effect, is the efficiency of TEG at .

Based on the parameters listed in Table 1, the impacts of some key factors (including phase change material, Thomson effect, the total number of TEEs (), heating source temperature (), the cross-sectional area of the semiconductor legs ()) on the TEG performance are discussed.

* 1. **Effect of Thomson effect**

The power output and electrical current of the TEG varying with the input heat rate with or without Thomson effect are compared in Fig. 2. It shows that  firstly increases and then decreases while  continuously decrease with  in the region of .In the regions of  or , TEG does not generate electrical power, so  and  equal to zero in these regions. Fig. 2 also shows that,, ,  and  of TEG without Thomson effect are larger than that of TEG with Thomson effect, while  is smaller than that of  with Thomson effect. The  with Thomson effect reaches 0.57 W, which is 50.68% lower than that of  with Thomson effect. Fig. 3 shows that  first increases and then decreases with the increase of , and the  with Thomson effect is 2.71%, which is 47.68% lower than that of  without Thomson effect. Generally, the TEG model with Thomson effect is closer to the real situation for the system [13, 14].

Q VS I P PhaseI VS YITA Phase

Fig. 4. Electrical current and power output varying with input heat rate with or without phase change material.

Fig. 5. Efficiency varying with current with or without phase change material.

* 1. **Effect of phase change material**

Fig. 4 shows the comparison of electrical current and power output varying with the input heat transfer rate by using phase-change material and a normal heat transfer system between heat source and TEG. It is found that , , ,  and  of TEG with phase change material are larger than that of TEG with normal heat transfer system, while  is smaller than the latter one. The  with phase change material reaches 0.56 W, which is 36.29% greater than that of TEG  with normal convection heat transfer system. Fig. 5 shows that  first increases and then decreases with the increase of , and the  with phase change material is 2.71%, which is 16.73% greater than that of  without phase change material. It is attributed to the fact that phase change heat transfer coefficient is much larger than that of coefficient with a normal heat transfer system, and the increase of convection heat transfer coefficient can lead to the growth of the hot side temperature of TEG based on Eq. (13), and thereby improving the efficiency and power output of TEG.

* 1. **Effect of the number of TEEs**

The performance of TEG is closely relevant to its configuration and the number of TEEs. A larger  represents more TEEs are applied, which is beneficial to improve the performance of TEG [28]. As shown in Fig. 6, , ,  and  increase, while  almost keeps constant as  increases from 15 to 25. The values of  are, respectively, 0.42 W, 0.57 W and 0.71 W when  equals to 15, 20 and 25. Fig. 7 shows that the  almost remains unchanged with the increase of  and the power output is maximum at maximum energy efficiency condition. Therefore, it is found that an increasing  can greatly improve the power output of TEG without reducing its efficiency.

Q VS I P nYITA VS P n

Fig. 6. Electrical current and power output varying with input heat rate under different number of TEEs.

Fig. 7. Power output varying with efficiency under different number of TEEs.

**Q VS I P ThYITA VS P Th**

Fig. 8. Electrical current and power output varying with input heat rate under different heat source temperature.

Fig. 9. Power output varying with efficiency under different heat source temperature.

* 1. **Effect of heat source temperature**

Based on Eq. (13), an increasing heat source temperature  can enhance the hot side temperature of TEG and thus influence its performance. As shown in Fig. 8, , ,  and  increase, while  almost remains unchanged as  increases. The values of  are, respectively, 0.40 W, 0.57 W and 0.76 W when  equals to 430 K, 450 K and 470 K. Fig. 9 shows the  grows from 2.68% to 3.03% when the  increases from 430 K to 470 K and the power output is maximum at maximum energy efficiency condition. Therefore, an increasing  can simultaneously improve the power output and efficiency of TEG. Thus, the proposed model may be applied to recover the waste heat from the fuel cell which operating temperature can be in the region of 430 K - 470 K, such as high-temperature polymer electrolyte membrane fuel cell [3], phosphoric acid fuel cell [10] and high-temperature proton exchange membrane fuel cell [2].

* 1. **Effect of the cross-sectional area of semiconductor legs**

Eqs. (8) and (9) show that with the increase of the cross-sectional area of the semiconductor legs , the electric resistance decreases and the electric conductance increases. The effects of  on the TEG performance are shown in Fig. 10. It is found that , , ,  and  increase as  increases from m2 to m2. The values of  are, respectively, 0.38 W, 0.57 W and 0.76 W when  equals to  m,  m2 and  m2. Fig. 11 reveals that the  almost remains constant as  increases and the power output is maximum at maximum energy efficiency condition. Therefore, an increasing  can greatly improve the power output of TEG without reducing the efficiency based on the parameters in Table 1.

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Fig. 10. Electrical current and power output varying with input heat rate under different cross-sectional area of semiconductor legs.

Fig. 11. Power output varying with efficiency under different cross-sectional area of semiconductor legs.

# **Conclusions**

In this paper, Thomson effect that is always ignored in previous studies is considered to evaluate the performance of TEG. Besides, a heat exchanger is put forward to better contact TEG to fuel cell, and phase change material is also used to improve the heat transfer between heat source and TEG. The influence of some key factors on the performance of TEG is revealed in detail. The main conclusions are as follows:

* The maximum power output with Thomson effect reaches 0.57 W, which is 50.68% lower than that of maximum power output without Thomson effect. The corresponding efficiency when power out reaches its maximum value is 2.71%, which is 47.67% lower than that of efficiency without Thomson effect.
* Phase change material is used to improve the heat transfer between the heat source and TEG, the maximum power output and the corresponding efficiency with phase change material are, respectively, 0.57 W and 2.71%, which are, respectively, 36.29% and 16.73% greater than that of maximum power output and efficiency with normal heat convection system.
* The maximum power output can be improved from 0.42 W to 0.71 W while the corresponding efficiency almost remains unchanged when the number of TEEs increases from 15 to 25.
* An increasing heat source temperature can simultaneously improve the power output and efficiency of TEG. The maximum power output can be raised from 0.40 W to 0.76 W while the corresponding efficiency grows from 2.68% to 3.03% as the heat source temperature increases from 430 K to 470 K.
* The maximum power output can be enhanced from 0.38 W to 0.76 W while the corresponding efficiency almost remains unchanged as the cross-sectional area of semiconductor legs increases from  m2 to  m2.
* The power output is always maximum at maximum energy efficiency condition.

Although the results of this study reveal that the TEG with appropriate phase change material is practical for recovering waste heat from fuel cell, and it can also offer some useful theoretical bases for the TEG-phase change material-fuel cell system; the power output and efficiency of TEG obtained is still relatively low. To further improve the performance of TEG, a heat exchanger filled with phase change material may be combined with a two-stage TEG to recover waste heat from fuel cell, which can be subject to future work.

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