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Detailed Modeling and Irreversible Transfer Process Analysis of a Multi-Element Thermoelectric Generator System

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Thermoelectric (TE) power generation technology, due to its several advantages, is becoming a noteworthy research direction. Many researchers conduct their performance analysis and optimization of TE devices and related applications based on the generalized thermoelectric energy balance equations. These generalized TE equations involve the internal irreversibility of Joule heating inside the thermoelectric device and heat leakage through the thermoelectric couple leg. However, it is assumed that the thermoelectric generator (TEG) is thermally isolated from the surroundings except for the heat flows at the cold and hot junctions. Since the thermoelectric generator is a multi-element device in practice, being composed of many fundamental TE couple legs, the effect of heat transfer between the TE couple leg and the ambient environment is not negligible. In this paper, based on basic theories of thermoelectric power generation and thermal science, detailed modeling of a thermoelectric generator taking account of the phenomenon of energy loss from the TE couple leg is reported. The revised generalized thermoelectric energy balance equations considering the effect of heat transfer between the TE couple leg and the ambient environment have been derived. Furthermore, characteristics of a multi-element thermoelectric generator with irreversibility have been investigated on the basis of the new derived TE equations. In the present investigation, second-law-based thermodynamic analysis (exergy analysis) has been applied to the irreversible heat transfer process in particular. It is found that the existence of the irreversible heat convection process causes a large loss of heat exergy in the TEG system, and using thermoelectric generators for low-grade waste heat recovery has promising potential. The results of irreversibility analysis, especially irreversible effects on generator system performance, based on the system model established in detail have guiding significance for the development and application of thermoelectric generators, particularly for the design and optimization of TE modules.

Key words: Multi-element thermoelectric generator, modeling, irreversible transfer process, second-law-based thermodynamic analysis

INTRODUCTION

Thermoelectric (TE) power generation, as an entirely solid-state energy conversion technology, directly transforms thermal energy into electrical energy by employing thermoelectric materials. A thermoelectric power converter has no moving parts, and is compact, quiet, highly reliable, and environmentally friendly. Due to these advantages, this generation technology is presently becoming a noteworthy research direction.

However, wide application of thermoelectric power generation has been limited because of its relatively low heat-to-electricity conversion efficiency. Bell[1] points out that there are two important pathways which will lead to additional applications for thermoelectric devices. One will be improving

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the intrinsic efficiencies of the TE materials, and many efforts are underway to accomplish this. Another is to improve the way in which existing TE devices are currently used, since improvement of the intrinsic efficiencies of TE materials at device level has yet to be demonstrated. Recently, Chen et al.[2] describe a technological change represented by the integration of thermoelectric generators (TEG) into combined heat and power production (CHP) energy systems and how this approach affects energy consumption by promoting efficiency improvements. It is found that this system, using the TEG as a simple and reliable waste heat converter, is a good example TE application.

Regarding system analysis and optimization, Rowe and Gao[3] developed a procedure to assess the potential of TE modules used for electrical power generation. Chen and Wu[4] used an irreversible model to study the performance of a thermoelectric generator with external and internal irreversibility. They analyzed the performance of a single-element TEG. However, in practice, a thermoelectric generator is composed of many fundamental thermoelectric elements; i.e., it is a multi-element device. Hence, Chen et al.[5,7] and Pan et al.[6] have undertaken research on system analysis and optimization of multi-element TE devices.

Many researchers[2,4–11] conduct their performance analysis and optimization of TE devices and the related applications based on the generalized thermoelectric energy balance equations. These generalized TE equations involve the internal irreversibility of Joule heating inside the thermoelectric device and heat leakage through the thermoelectric couple leg. However, it is assumed that the TEG is thermally isolated from the surroundings except for the heat flows at the cold and hot junctions.[9]

Since the TEG is a multi-element device in practice, being composed of many fundamental TE couple legs, the effect of heat transfer between the thermoelectric couple leg and the ambient environment is not negligible. In this paper, detailed modeling of a TEG taking into account the phenomenon of energy loss from the thermoelectric couple leg is reported. Moreover, based on the new derived TE equations and by means of a second-law-based thermodynamic analysis, characteristics of a multi-element thermoelectric generator with irreversibility are investigated.

SYSTEM MODELING

A general thermoelectric generator with load resistance R_L connected is comprised of several thermoelectric elements (Fig. 1), each of which consists of p- and n-type semiconductor legs working between high- and low-temperature heat reservoirs at temperatures of T_1 and T_2, respectively.

Q_H and Q_C in Fig. 1 represent the heat absorbed by the generator from the high-temperature reservoir and released to the low-temperature reservoir per unit time, respectively. Owing to the Peltier effect occurring at the end of the semiconductor leg, the heat flux in each thermoelectric element of the generator (one pair of p- and n-type semiconductor legs) absorbed from the high-temperature reservoir (Q_{ph}) and released to the low-temperature reservoir (Q_{pc}) can be shown to be

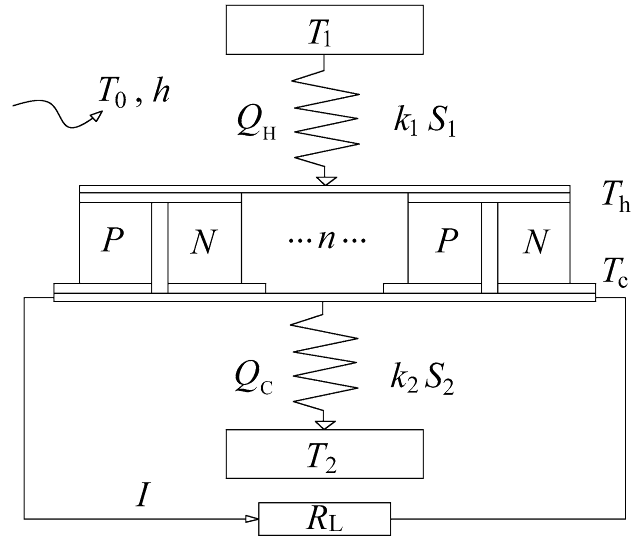

Fig. 1. Schematic diagram of a multi-element thermoelectric generator.

$$Q_{ph} = \alpha I T_h, \tag{1}$$

$$Q_{pc} = \alpha I T_c, \tag{2}$$

where I is the electric current in the generator circuit, and T_h and T_c are the hot- and cold-side temperature of the generator. In addition, α_p and α_n are the Seebeck coefficients of the p- and n-type semiconductor legs, respectively, and $\alpha = \alpha_p - \alpha_n$.

In Fig. 2, Q_p is the heat flux in the p-type leg, and Q_n is the heat flux in the n-type leg. Q is the sum of Q_p and Q_n, which flows from the hot side of the legs to the cold side. Chen et al.[9] have conducted a detailed derivation for the generalized thermoelectric energy balance equations. As they mentioned and as usually adopted in one-dimensional models, we also here assume that the electric resistivities ρ_p and ρ_n, the thermal conductivities k_p and k_n, and α_p and α_n of the p- and n-type semiconductor materials are independent of temperature. Hence, the Thomson effect is negligible. S_p and S_n are the uniform cross-sectional areas of the p- and n-type semiconductor legs, respectively. Manufacturing requirements usually dictate that the lengths of the two legs be identical, especially in TE module production, and this length is denoted here by L.

However, previous work assumed that the TEG was thermally isolated from the surroundings except for the heat flows at the cold and the hot

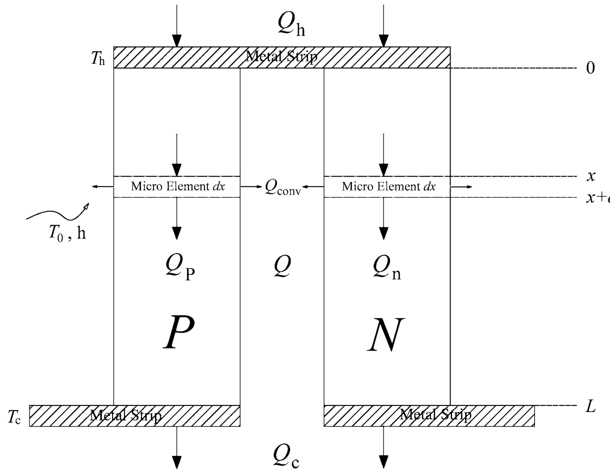

Fig. 2. Schematic representation of a pair of TE legs.

junctions. Since the thermoelectric generator is a multi-element device in practice, being composed of many fundamental TE couple legs, the effect of heat transfer between the TE leg and the ambient environment is not negligible. Goldsmid[12] assumed that some thermal insulation material filled the gap between the thermocouples and therefore analyzed the heat losses using the heat conduction method. However, in practice, there is no thermal insulation material in the gap between the semiconductor legs in a thermoelectric module. Accordingly, we assume that the heat losses occur mainly through heat convection and therefore address it by the method of convection rather than conduction.

This work focuses on performance analysis of low-temperature applications of the TEG. According to heat transfer theory, in low-temperature conditions, the amount of radiative heat transfer is very small, in contrast to heat convection. Moreover, except for the limited radiative losses from low-temperature heat sources, there is an extremely small amount of radiation loss from the ambient air due to its extremely low radiation ability. So, the effect of radiative losses is neglected in this work.

Consequently, in terms of energy conservation, the equation governing heat transfer of the infinitesimal element with length $\mathrm{d}x$ in the p-type leg in steady state can be written as

$$Q_p(x) + I^2\frac{\rho_p}{S_p}\mathrm{d}x = Q_p(x+\mathrm{d}x) + hP\left[T_p(x) - T_0\right]\mathrm{d}x. \tag{3}$$

Then, Eq. (3) can be expressed as follows:

$$\begin{aligned}\mathrm{d}Q_p(x) &= Q_p(x+\mathrm{d}x) - Q_p(x)\\ &= I^2\frac{\rho_p}{S_p}\mathrm{d}x - hP[T_p(x) - T_0]\mathrm{d}x,\end{aligned} \tag{4}$$

where h is the heat transfer coefficient between the TE leg and the ambient environment and T_0 is the ambient temperature. To simplify the analysis and derivation, we assume that T_0 is a constant. This is because the surrounding temperature is only slightly affected by the heat of the hot and the cold heat reservoirs, since the specific heat capacity of the large space (characterized by T_0) is assumed to be infinite. Also, P represents the circumference of the leg. We usually assume the circumferences of the p- and n-type legs to be identical and not to change with position x. Q_p and T_p refer to the conduction heat flow and the temperature profile of the p-type leg, respectively, which are functions of position x. The two terms on the right-hand side of Eq. (4) are the Joule heat generation rate, acting as an internal heat source term, and the heat transfer rate, resembling a heat sink term. The term $Q_p(x + \mathrm{d}x) - Q_p(x)$ represents the increase of the heat flow from the inlet at position x to the outlet at position $x + \mathrm{d}x$.

By integrating Eq. (4) from position 0 to x, we get

$$Q_p(x) - Q_p(0) = I^2\frac{\rho_p}{S_p}x - hP\int_0^x\left[T_p(x) - T_0\right]\mathrm{d}x. \tag{5}$$

Here, it is assumed that $T_p(x)$ is a function with linear distribution in the range of position 0 to x. Thus, we find

$$\begin{aligned}\int_0^x T_p(x)\mathrm{d}x &= \frac{T_p(0) + T_p(x)}{2}x\\ &= \frac{T_\mathrm{h} + T_p(x)}{2}x \quad (0 \le x \le L).\end{aligned} \tag{6}$$

If we take Eq. (6) and the boundary condition at the position L into account, the following two equations can be obtained based on Eq. (5):

$$Q_p(x) - Q_p(0) = I^2\frac{\rho_p}{S_p}x - hP\left[\frac{T_\mathrm{h} + T_p(x)}{2} - T_0\right]x, \tag{7}$$

$$\begin{aligned}Q_p(L) &= Q_p(0) + I^2\frac{\rho_p}{S_p}L - hP\left[\frac{T_\mathrm{h} + T_p(L)}{2} - T_0\right]L\\ &= Q_p(0) + I^2\frac{\rho_p}{S_p}L - hP\left[\frac{T_\mathrm{h} + T_\mathrm{c}}{2} - T_0\right]L.\end{aligned} \tag{8}$$

According to Fourier's law of heat conduction, the relation between the heat flow and the temperature gradient is

$$Q_p(x) = -k_pS_p\frac{\mathrm{d}T_p(x)}{\mathrm{d}x}. \tag{9}$$

Taking Eq. (9) into account, we get

$$\begin{aligned}&k_pS_p\frac{\mathrm{d}T_p(x)}{\mathrm{d}x} + Q_p(0) + I^2\frac{\rho_p}{S_p}x\\ &\quad - hP\left[\frac{T_\mathrm{h} + T_p(x)}{2} - T_0\right]x = 0.\end{aligned} \tag{10}$$

Then, Eq. (10) can be integrated to yield

$$\int_0^x k_p S_p \mathrm{d}T_p(x) + \int_0^x Q_p(0)\mathrm{d}x + \int_0^x I^2 \frac{\rho_p}{S_p} x\mathrm{d}x - \int_0^x hP\left[\frac{T_\mathrm{h} + T_p(x)}{2} - T_0\right] x\mathrm{d}x = 0, \quad (11)$$

$$k_p S_p [T_p(x) - T_p(0)] + Q_p(0)x + \frac{I^2\rho_p}{2S_p}x^2 - hP\int_0^x \left[\frac{T_\mathrm{h} + T_p(x)}{2} - T_0\right] x\mathrm{d}x = 0. \quad (12)$$

For the purpose of simplifying the integration process, we adopt the assumption

$$T_p(x) = T'_p(x) = \text{const.} \quad (0 \le x \le L). \quad (13)$$

So, Eq. (12) becomes

$$k_p S_p [T_p(x) - T_\mathrm{h}] + Q_p(0)x + \frac{I^2\rho_p}{2S_p}x^2 - \frac{hP}{2}\left[\frac{T_\mathrm{h} + T'_p(x)}{2} - T_0\right] x^2 = 0. \quad (14)$$

If we use the boundary condition at the cold side, we find

$$T'_p(x) = T_p(L) = T_\mathrm{c}, \quad (15)$$

$$k_p S_p (T_\mathrm{c} - T_\mathrm{h}) + Q_p(0)L + \frac{I^2\rho_p}{2S_p}L^2 - \frac{hP}{2}\left(\frac{T_\mathrm{h} + T_\mathrm{c}}{2} - T_0\right) L^2 = 0. \quad (16)$$

By sorting the equation above, the following can be derived:

$$\frac{k_p S_p}{L}(T_\mathrm{c} - T_\mathrm{h}) + Q_p(0) + \frac{I^2\rho_p}{2S_p}L - \frac{hPL}{2}\left(\frac{T_\mathrm{h} + T_\mathrm{c}}{2} - T_0\right) = 0, \quad (17)$$

$$\begin{aligned} Q_p(0) &= \frac{k_p S_p}{L}(T_\mathrm{h} - T_\mathrm{c}) - \frac{I^2\rho_p}{2S_p}L + \frac{hPL}{2}\left(\frac{T_\mathrm{h} + T_\mathrm{c}}{2} - T_0\right) \\ &= K_p(T_\mathrm{h} - T_\mathrm{c}) - 0.5I^2R_p + 0.5hPL\left(\frac{T_\mathrm{h} + T_\mathrm{c}}{2} - T_0\right), \end{aligned} \quad (18)$$

where K_p is the thermal conductance of the p-type leg, R_p is the internal electric resistance of the p-type leg, and

$$K_p = \frac{k_p S_p}{L}, \quad (19)$$

$$R_p = \frac{\rho_p}{S_p}L. \quad (20)$$

To obtain a concise expression, we use Q_pconv to represent the rate of heat dissipation of the p-type leg by convection,

$$Q_\mathrm{pconv} = hPL\left(\frac{T_\mathrm{h} + T_\mathrm{c}}{2} - T_0\right). \quad (21)$$

Inserting Eq. (21) into Eq. (18), we find

$$Q_p(0) = K_p(T_\mathrm{h} - T_\mathrm{c}) - 0.5I^2R_p + 0.5Q_\mathrm{pconv}. \quad (22)$$

According to Eq. (8), the equation for the heat flux at the cold junction is

$$Q_p(L) = K_p(T_\mathrm{h} - T_\mathrm{c}) + 0.5I^2R_p - 0.5Q_\mathrm{pconv}. \quad (23)$$

We can employ the same method and the same boundary conditions to derive the expression of the heat flow Q_n in the same form for the n-type leg. Consequently, the general equations for a single-element TEG (composed of only one pair of TE legs) are

$$\begin{aligned} Q(0) &= Q_p(0) + Q_n(0) \\ &= K(T_\mathrm{h} - T_\mathrm{c}) - 0.5I^2R + 0.5Q_\mathrm{conv}, \end{aligned} \quad (24a)$$

$$\begin{aligned} Q(L) &= Q_p(L) + Q_n(L) \\ &= K(T_\mathrm{h} - T_\mathrm{c}) + 0.5I^2R - 0.5Q_\mathrm{conv}, \end{aligned} \quad (24b)$$

where K and R are the total thermal conductance and the internal electric resistance of the single-couple thermoelectric generator, respectively, and

$$K = \frac{k_p S_p}{L} + \frac{k_n S_n}{L}, \quad (25)$$

$$R = \frac{\rho_p}{S_p}L + \frac{\rho_n}{S_n}L. \quad (26)$$

Similarly, we use Q_conv to represent the rate of heat dissipation of the pair of TE legs by convection,

$$Q_\mathrm{conv} = 2hPL\left(\frac{T_\mathrm{h} + T_\mathrm{c}}{2} - T_0\right). \quad (27)$$

Considering the Peltier effect occurring at the hot and the cold junctions, expressed by Eq. (1) and Eq. (2), Eqs. (24a) and (24b) can now be changed to

$$Q_h = Q_{ph} + Q(0) = \alpha I T_h + K(T_h - T_c) - 0.5I^2R + 0.5Q_{conv}, \quad (28a)$$

$$Q_c = Q_{pc} + Q(L) = \alpha I T_c + K(T_h - T_c) + 0.5I^2R - 0.5Q_{conv}. \quad (28b)$$

Equations (28a) and (28b) are the revised generalized thermoelectric energy balance equation considering the effect of heat transfer between the TE couple leg and the ambient environment. If the term $0.5Q_{conv}$ is removed from Eqs. (28a) and (28b), we obtain the generalized thermoelectric energy balance equations on which most previous work is based.[2,4–11]

On account of the heat resistance between the heat reservoirs and the generator, the heat exchange rate is limited, namely to a finite rate heat transfer. By employing Newton's law of heat transfer and the analysis above, the total heat flux of the multicouple TEG, Q_H and Q_C can be expressed as follows:

$$Q_H = k_1S_1(T_1 - T_h) = nQ_h = n[\alpha I T_h + K(T_h - T_c) - 0.5I^2R + 0.5Q_{conv}], \quad (29a)$$

$$Q_C = k_2S_2(T_c - T_2) = nQ_c = n[\alpha I T_c + K(T_h - T_c) + 0.5I^2R - 0.5Q_{conv}], \quad (29b)$$

where k_1 and k_2 are the heat transfer coefficients between the TEG and the heat reservoirs on the hot and cold sides, respectively. All thermal contact effects at the interfaces are included in k_1 and k_2. S_1 and S_2 are the heat transfer surface areas between the TEG and the heat reservoirs on the hot and cold sides, respectively, and n is the number of TE couples in the generator.

ANALYSIS OF IRREVERSIBLE TRANSFER PROCESSES

As we know, thermoelectric power generation involves several energy transfer processes. Actually, there are four macro processes in the TE couple legs which have been revealed by the derived TE energy balance equation, i.e., the Peltier effect, the Joule effect, heat conduction, and heat convection.

The Peltier effect, as a basic thermoelectric effect, acts at both junctions of the TE legs, as expressed by Eq. (1) and Eq. (2), respectively. The Joule effect caused by the electric resistance of the TE materials R is just the generation of Joule heat throughout all the TE legs. Although Eqs. (28a) and (28b) seem to indicate that the Joule heat produced inside the leg flows equally to the hot and cold junctions, the transfer process of the Joule heat generated in the TEG is actually nothing but conduction,[9] if convection is not taken into account. All of the Joule heat flows toward the low-temperature heat reservoir according to Fourier's law of heat conduction.

In fact, from the detailed derivation process above, it is easy to find that the $0.5I^2R$ term in Eqs. (28a) and (28b) is the result of integration. Moreover, the factor 0.5 is not an approximation but rather a result of the assumption that the thermal and electric material properties are constant along the p- and n-type legs, which is also responsible for the appearance of the convective term $0.5Q_{conv}$ in Eqs. (28a) and (28b). Now, we discuss the effect of heat convection on TEG performance.

The power output of the multicouple TEG P_{out} can be written as

$$P_{out} = I^2R_L = \left(\frac{n\alpha\Delta T}{nR + R_L}\right)^2 R_L, \quad (30)$$

where $\Delta T = T_h - T_c$. P_{out} can also be expressed in terms of voltage output V_{out} as

$$P_{out} = V_{out}I = (n\alpha\Delta T - InR)I = n\alpha I\Delta T - I^2nR = \frac{n^2\alpha^2\Delta T^2}{nR + R_L} - \left(\frac{n\alpha\Delta T}{nR + R_L}\right)^2 nR. \quad (31)$$

Obviously, Eqs. (30) and (31) are equivalent. Consequently, the TEG energy conversion efficiency η can be defined as

$$\eta = \frac{P_{out}}{Q_H} = \frac{n\alpha I\Delta T - I^2nR}{n[\alpha I T_h + K(T_h - T_c) - 0.5I^2R + 0.5Q_{conv}]} = \frac{Q_H - Q_C - nQ_{conv}}{Q_H} = \frac{Q_h - Q_c - Q_{conv}}{Q_h}. \quad (32)$$

Now, we can find the influence of heat convection on the TEG performance more clearly from Eq. (32). On the one hand, the convection directly causes a part of the heat, which can be partly converted to electric power, before dissipating into the ambient environment. On the other hand, the convective term $0.5Q_{conv}$ in Eqs. (28a) and (28b) indirectly reduces the TEG energy conversion efficiency.

To quantitatively evaluate the effect of heat convection on TEG performance, as an example, we have considered a series of material and geometric properties (Seebeck coefficient $\alpha = 9.6774 \times 10^{-4}$ V K^{-1}, thermal conductance $K = 3.84 \times 10^{-3}$ W K^{-1}, electric resistance $R = 0.086\ \Omega$, uniform TE leg dimensions 2 mm × 2 mm × 3 mm, and number of TE couples $n = 31$) as measured from a commercial TE module to carry out a performance analysis based on the system model established.

Furthermore, second-law-based thermodynamic analysis (exergy analysis) has been applied to the irreversible heat transfer process in particular. As we know, the consideration of energy quality leads to the concept of exergy. Exergy is a measure that indicates the degree to which energy is convertible to other forms of energy. It is a measure of the quality level of energy. To make this clear, all kinds of energy can be classified into different grades in accordance with its capacity to be converted into other forms of energy. For example, as is well known, electric power energy is the "first energy" in human society. This is not only because it is easy to transmit and clean, but also because it can be completely converted into any other form of energy without any external energy consumption. Hence, we consider that electric power energy is a kind of high-grade energy, and its exergy is equal to its energy.

However, it is impossible to convert thermal energy completely to electric power energy without any external energy consumption, as revealed by the second law of thermodynamics. Generally speaking, the efficiency of a heat engine is less than 30%, and even the efficiency of an advanced thermal power plant is generally no more than 50%. The maximum efficiency of a heat engine is limited by the efficiency of its corresponding Carnot cycle. The Carnot cycle efficiency of a heat engine is

$$\eta_{\text{Carnot}} = 1 - \frac{T_{\text{c}}}{T_{\text{h}}}, \tag{33}$$

where T_{c} is the temperature of the cold heat reservoir and T_{h} is the temperature of the hot heat reservoir.

As a result, we consider that thermal energy is a kind of low-grade energy, and its exergy is only equal to its partial energy which could be converted to any other forms of energy without any external energy consumption. That is to say, the amount of exergy of the heat engine can be expressed as

$$E_{\text{x}} = \eta_{\text{Carnot}} Q_{\text{H}} = \left(1 - \frac{T_{\text{c}}}{T_{\text{h}}}\right) Q_{\text{H}}, \tag{34}$$

where Q_{H} is the amount of heat input from the hot heat reservoir.

Energy efficiency η does not include the availability of the converted energy. However, exergy efficiency includes the quality level of the converted energy. In this investigation, we define

$$\eta_{\text{x}} = \frac{P_{\text{out}}}{E_{\text{x}}} = \frac{P_{\text{out}}}{\left(1 - \frac{T_{\text{c}}}{T_{\text{h}}}\right) Q_{\text{H}}} = \frac{\eta}{1 - \frac{T_{\text{c}}}{T_{\text{h}}}} \tag{35}$$

as the TEG exergy efficiency.

First, for the purpose of investigating the effect of heat convection on the TEG performance, the heat transfer coefficient h is chosen as a variable while a rated condition (T_{c} = 313 K, T_0 = 298 K, and R_{L} = 2.7 Ω is the matching resistance) is set as a benchmark for the analysis. It is found from Eq. (31) that the system power output P_{out} is not affected by the irreversible heat convection process. However, by applying this methodology based on Eqs. (32) and (35), comparisons of the energetic and exergetic efficiencies can be made.

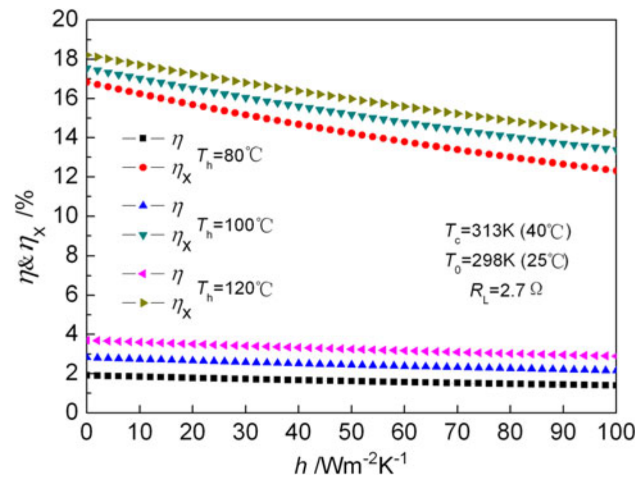

Fig. 3. Effect of h and ΔT on TEG efficiency characteristics.

As shown in Fig. 3, the existence of heat convection between the TE legs and the ambient environment reduces the energy conversion efficiency η and the exergy efficiency η_{x} of this TEG system. Moreover, both the rate and the magnitude of the reduction are much larger for η_{x} than for η, especially when the value of the heat transfer coefficient h is within the range of natural convection (0 W m^{-2} K^{-1} to 10 W m^{-2} K^{-1}). This effect shows that the value of the convective heat flow Q_{conv} is very small compared with that of the total heat flow Q_{H}. However, the existence of the irreversible heat convection process does cause a large loss of heat exergy. In addition, an important feature of the TEG in low-temperature (low-grade) thermal energy utilization, namely high exergy efficiency, is illustrated in Fig. 3, though the energy conversion efficiency is relatively low. At the same time, from the performance comparison of three different work conditions (T_{h} = 353 K, 373 K, and 393 K, respectively), it is easy to find that increasing the temperature difference can enhance the TEG system performance, which is consistent with common sense.

From the point of view of battery applications, as shown in Fig. 4, the voltage–current characteristic of this TEG is the same as that of conventional batteries. Like a typical physical battery, the thermoelectric power generator also has the feature of impedance matching. It is easy to find the maximum power output point in Fig. 5 when the value of the load resistance R_{L} is equal to the internal electric resistance value 2.7 Ω of this TEG. Besides, the effect of the load resistance on TEG efficiencies is analyzed and illustrated in Fig. 5 simultaneously. Obviously, the feature of impedance matching applies equally to efficiencies, although the maximum efficiency points occur when the value of the

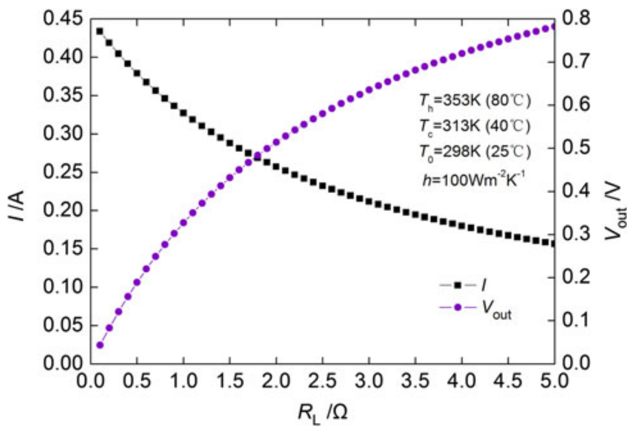

Fig. 4. Effect of R_L on TEG voltage and current characteristics.

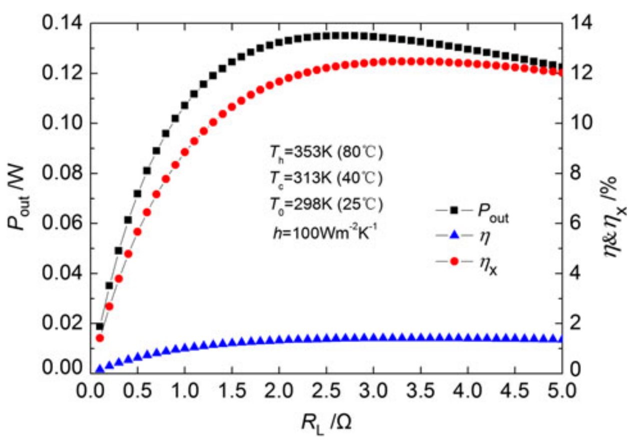

Fig. 5. Effect of R_L on TEG power output and efficiency characteristics.

load resistance is slightly larger than the internal electric resistance value 2.7 Ω of this TEG. Moreover, the rate and magnitude of the reduction of η_x are much larger than those of η once the load resistance value deviates from the matching resistance value, especially when the value of R_L is smaller than the matching resistance value. This characteristic is an effective guide for TEG optimization and applications.

CONCLUSIONS

Based on basic theories of thermoelectric power generation and thermal science, detailed modeling of a thermoelectric generator taking into account the phenomenon of energy loss from the TE couple leg has been carried out. Revised generalized thermoelectric energy balance equations considering the effect of heat transfer between the TE couple leg and the ambient environment have been derived.

According to the analysis of irreversible transfer processes through the method of second-law-based thermodynamic analysis (exergy analysis), it is found that the energy loss from the TE couple legs is very small in quantity compared with the total heat that the TEG absorbs. However, the existence of the irreversible heat convection process does cause a large loss of heat exergy in this TEG, which must be taken into consideration in system optimization and applications.

It is also found that utilizing thermoelectric generators for low-grade waste heat recovery has promising potential, namely high exergy efficiency, although the TEG energy conversion efficiency is relatively low. This reveals that TEGs can convert a relatively large amount of low-grade thermal energy to electrical energy, which cannot be done by conventional energy utilization forms, e.g., internal combustion engines and gas/steam turbine generators. In addition, for the purpose of enhancing TEG system performance in applications, the load resistance value should be equal to the matching (internal) resistance, or at least greater than it, to avoid substantial degradation of system power output and efficiencies.

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