Heat reliability analysis of thermoelectric generators (TEG) based on heat transfer process

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Abstract. Thermoelectric generator (TEG) for output power is generated in different temperature. Its heat reliability is effect on the life length. In this paper a one-dimensional transient heat transfer model of thermoelectric generator has been proposed and the temperature field of TEG has been given. The reliability model of TEG has been established for analyzing the TEG’s life by considering the TEG structure compositions. The TEG life length has been studied under different heat flux per unit time conditions according to reliability distribution function. The results show the output power of TEG is increased when the temperature of TEG structure is increasing. But, the TEG life length is reduced with increasing temperature. Therefore, the TEG temperature is large effect on the life length of TEG.

1. Introduction
Energy recovery has been a hot issue in all kinds of engines in recent years. In the case of waste heat recovery the thermoelectric generator (TEG) is a device for directly converting thermal energy into electrical energy[1]. The TEGs have many advantages such as no moving mechanical parts, long-lived, quiet, environmentally friendly and requiring little maintenance[2,3]. TEG can recover engine waste heat in a straightforward manner[4,5,6]. Du et al.[7] developed a thermoelectric generator (TEG) model coupled with exhaust and cooling channels for an exhaust-based TEG (ETEG) system, and then investigated the influence of the cooling type, coolant flow rate, length, number and location of bafflers. Ref.[8] provided useful information on optimization of the TEG system, including optimization of the system layout, and configuration of TEG and predicted the heat transfer characteristics of thermoelectric modules by theoretical analysis. Li[9] proposed one-dimensional transient heat transfer model of thermoelectric generator, and the analysis of the performance of transient heat transfer and power generating was implemented.

Reliability is a dynamic concept which is applicable to many fields. The Failure In Time (FIT) rate of a device represents the number of expected failures in one billion (10^9) device-hours of operation and this parameter is widely diffused in the semiconductor industry[10-12]. The reliability prediction, for example, makes it possible to decide whether to duplicate a safety critical system or to put it in avoiding conditions, with great savings in terms of weight and power consumption[13-17]. However, the TEG heat reliability is effect on its life length because of the TEG working in different temperature. There hasn’t been an abundance of literature and researches about TEG life length in different temperature.
In this paper, a one-dimensional transient heat-transfer model of thermoelectric generator is proposed and the temperature field of TEG is given firstly according to heat transfer and thermal conversion. And there is part of the heat would be converted to electric energy. The reliability model of TEG is established for analyzing the TEG’s life. And then The TEG life length has been studied under different heat flux conditions according to reliability distribution function. The results show the output power of TEG is increased but its life length is reduced with increasing temperature.

2. Analysis Model

2.1. TEG heat-transfer model

Configuration of the TEG is illustrated in Figure 1. The heat is absorbed by the hot side of TEG and a part of the heat is converted electrical power, the rest of heat is rejected to environment. The TEG structure is consisted of Al₂O₃ ceramics plate, Al sheet metal and Bi₂Te₃ semiconductor material. Most importantly, on top of every one of these (copper) interconnections are: a p- and an n-type thermoelectric leg, which the combination of a p- and an n-type leg is called a thermocouple. Inside the thermoelectric generator, many thermocouples are connected in series and thermally connected in parallel[18].

![Figure 1. Schematic drawing of a thermoelectric generator](image1)

A typical one-dimensional transient heat-transfer model of TEG is shown in Figure 2. The heat is absorbed by the hot side of TEM (thermoelectric model) across ceramics plate, sheet metal and semiconductor, respectively and taking into account the Seebeck effect, Peltier effect, Joule heating.

![Figure 2. One-dimensional transient heat-transfer model of thermoelectric generator](image2)

According to the infinitesimal dx of TEG by energy conservation law, the differentiating energy balance equation for the thermoelectric elements is:
Here, \( \rho \)—density, \( c \)—heat capacity, \( T \)—temperature, \( k \)—thermal conductivity, \( r_3 \)—electrical resistivity, \( I \)—current, \( A \)—cross-sectional area, \( j \)—different structure material.

The initial condition for the differential equation of the thermoelectric element is original temperature about environment, it is:

\[ t = 0, I(0, x) = T_{th} \]  \hspace{1cm} (2.2)

The boundary conditions are included of the cold side heat flux per unit time and the hot side heat convection which is decided by Newton Cooling Principle. They are:

\[
\begin{align*}
    x &= 0, -k_j \frac{\partial T}{\partial x}_{x=0} = q \\
    x &= L, -k_j \frac{\partial T}{\partial x}_{x=L} = h_{eff}(T - T_{th})
\end{align*}
\]  \hspace{1cm} (2.3)

Here, \( q \) is the heat flux per unit time, \( L \) is the length of TEG from hot side to cold side, \( h_{eff} \) is the convection heat transfer coefficient, \( T_{th} \) is the environmental temperature.

2.2. TEG life length analysis

The ceramics plate, sheet metal, p- and n- semiconductor structure are the weak wastage materials in TEG’s life length. Therefore, their reliability functions are in exponential distribution according to the structure characteristics. They are:

\[
R_1(t) = e^{-\lambda_1 t}, \quad R_2(t) = e^{-\lambda_2 t}, \quad R_3(t) = e^{-\lambda_3 t}
\]  \hspace{1cm} (2.4)

Here, \( t \) is time, \( R_1, R_2, R_3 \) are the ceramics plate, the sheet metal and the semiconductor structure reliabilities, respectively, \( \lambda_1, \lambda_2, \lambda_3 \) are the ceramics plate, the sheet metal and the semiconductor structure failure rates, respectively.

The TEG system reliability model is called series type, so the TEG reliability function is:

\[ R(t) = e^{-(\lambda_1 + \lambda_2 + \lambda_3)t} \]  \hspace{1cm} (2.5)

Therefore, the TEG life length is calculated under the reliability. It is:

\[ t = -\frac{\ln R(t)}{(\lambda_1 + \lambda_2 + \lambda_3)} \]  \hspace{1cm} (2.6)

The TEG works in different temperature and its life length is changed in different temperature. The TEG’s structure characteristic has been large changed when the temperature is increasing. Meanwhile, the structure failure rate is increased, so there has been:

\[ \lambda_1 = f_1(T), \quad \lambda_2 = f_2(T), \quad \lambda_3 = f_3(T) \]  \hspace{1cm} (2.7)

Here, \( T \) is the temperature.

the failure rate of TEG’s structures is increased in exponential approximatively according to the structure performance changing with increasing temperature. So the relation with failure rate and temperature is:

\[ \lambda = e^{-aT+b} \]  \hspace{1cm} (2.8)
Here, \( a, b \) are the coefficients for confirming. Therefore, the ceramics plate, the sheet metal and the semiconductor structure failure rates are expressed as:

\[
\lambda_1 = e^{-a T + b}, \quad \lambda_2 = e^{-a T + b}, \quad \lambda_3 = e^{-a T + b}
\] (2.9)

And Eq. (2.9) is substituted in Eq. (2.6) for calculating the TEG life length.

\[
t = -\frac{1}{\ln R(t)} \left( \frac{e^{-a T + b}}{e^{-a T + b}} + e^{-a T + b} \right)
\] (2.10)

3. Results and Discussion

The heat transfer analysis of the TEG system is based on the heat equilibrium equations and the output power of TEG is in the maximum way. The geometric parameters of TEM are presented in Table 1 and the main physics parameters for TEM are shown in Table 2.

**Table 1 Main geometric parameters of the TEM**[18]

| Parameter                                | Value |
|------------------------------------------|-------|
| Length of p- and n- thermoelectric leg   | 9mm   |
| Thickness of sheet metal                 | 1mm   |
| Thickness of ceramics plate              | 2mm   |
| cross-sectional area                     | 2mmx2mm |

**Table 2 Main physics parameters for TEM**[18]

| Nomenclature          | Parameter                                | Value     |
|-----------------------|------------------------------------------|-----------|
| Thermoelectric leg    | Seebeck coefficient \( \alpha \)/V·K\(^{-1} \) | 2.12×10\(^{-4} \) |
|                       | Density \( \rho \)/kg·m\(^{-3} \)         | 10922.08  |
|                       | Specific heat \( c_3 \)/J·(kg·K\(^{-1} \) | 190       |
|                       | Thermal conductivity \( k_3 \)/W·(m·K\(^{-1} \) | 0.3       |
|                       | Electrical resistivity \( r_3 \)/Ω·m       | 1.05×10\(^{-4} \) |
| Sheet metal           | Density \( \rho_2 \), \( \rho_4 \)/kg·m\(^{-3} \) | 2700      |
|                       | Specific heat \( c_2 \), \( c_4 \)/J·(kg·K\(^{-1} \) | 795       |
|                       | Thermal conductivity \( k_2 \), \( k_4 \)/W·(m·K\(^{-1} \) | 130       |
| Ceramics plate        | Density \( \rho_1 \), \( \rho_5 \)/kg·m\(^{-3} \) | 3800      |
|                       | Specific heat \( c_1 \), \( c_5 \)/J·(kg·K\(^{-1} \) | 775       |
|                       | Thermal conductivity \( k_1 \), \( k_5 \)/W·(m·K\(^{-1} \) | 2.5       |

The environment temperature is set 300K for analyzing the TEM heat transfer process. There are four conditions that the heat flow rates are 20, 60, 100, 140 kW/m\(^2\) on the hot side TEM and the cold side condition is 2000 W/(m\(^2\)·K). The external circuit electric resistance is equal to internal resistance about 2.1125×10\(^{-2}\) Ω.

Figure 3 shows the distribution of the temperature about considering Joule heating and no Joule heating in different hot side conditions when 10 minute which it makes stable situation. The temperature has been large changed with the heat flow rate increasing. The highest temperatures of TEM’s different structures are shown in Table 3.
Figure 3. Temperature distribution in 10min under different hot conditions[18]

Table 3 The highest temperatures of TEM’s different structures

| Hot side condition | Ceramics plate | Sheet metal | Thermoelectric leg |
|--------------------|----------------|-------------|--------------------|
| 20kW/m²            | 486K           | 453K        | 450K               |
| 60kW/m²            | 740K           | 685K        | 681K               |
| 100kW/m²           | 943K           | 864K        | 857K               |
| 140kW/m²           | 1120K          | 1010K       | 1000K              |

The failure rate of the ceramics plate, the sheet metal and the semiconductor is about $10^{-8}\text{h}^{-1}$ according to the failure rate of welding spot at normal temperature. The ceramics plate (Al₂O₃) melting point temperature is about 2327K and the sheet metal (Al), the semiconductor (Bi₂Te₃) are about 933K, 858K, respectively. TEG would be not working in these temperatures. Therefore, the coefficients a, b from Eq. (2.9) can be confirmed. The failure rate function of the ceramics plate, the sheet metal and the semiconductor structure with changing temperature are presented in Eq. (2.11). Figure 4 shows the distribution of the TEM structure failure rate when the structure is borne in different temperature.
\begin{align}
\lambda_1 &= e^{0.10 \times 10^{-3} \tau - 21.18} \\
\lambda_2 &= e^{0.0296 \tau - 27.15} \\
\lambda_3 &= e^{0.0337 \tau - 28.31} 
\end{align}
(2.11)

**Figure 4.** The failure rate distribution under different temperature

When the hot side TEM condition is 140 kW/m², the temperature of the sheet metal and the semiconductor structure borne is exceeded TEG working temperature. Therefore, TEG would be damaged in the condition of 140 kW/m². When the hot side TEM conditions are 20, 60, 100kW/m², respectively, the highest temperatures which TEM’s different structures would been borne are shown in Table 3. So the failure rate function of the ceramics plate, the sheet metal and the semiconductor structure would be obtained according to the working temperature and the TEG life length would be calculated. It is assumed that the TEG reliability is about 0.8. The parameters of TEM’s in different hot side conditions are shown in Table 4.

**Table 4** The parameters of TEM’s in different hot side conditions

| Hot side condition | Ceramics plate (°C) | Sheet metal (°C) | Thermoelectric leg (°C) | \(\lambda_1 + \lambda_2 + \lambda_3\) | TEG life length (h) | TEM power (W) |
|-------------------|---------------------|-----------------|-------------------------|-------------------------------|-------------------|--------------|
| 20 kW/m²         | 486K                | 453K            | 450K                    | 2.300 \times 10^{-6}         | 96999.4           | 0.0076       |
| 60 kW/m²         | 740K                | 685K            | 681K                    | 3.604 \times 10^{-3}         | 61.9              | 0.0475       |
| 100 kW/m²        | 943K                | 864K            | 857K                    | 1.095                         | 0.2               | 0.0932       |

With the temperature of TEM structure increasing, the TEG life length is decreased seriously. When the ceramics plate, the sheet metal and the semiconductor structure working temperature are 486K, 453K and 450K, respectively, the TEG working life length hour after hour is about 96999.4h. However, the TEG working life length is only 0.2h with the temperature of TEM structure as 943K, 864K and 857K, respectively. But, the power of TEM would be increased with increasing temperature and it is presented in table 4.
4. Conclusions

One-dimensional transient heat-transfer model of thermoelectric generator for power generation system is constructed for analyzing the TEG working temperature. The reliability model of TEG is established for calculating the TEG’s working life length and the computational model to analyze the system is developed using discretization method. The following conclusions are drawn from the investigation in this paper:

The TEG life length has been studied under different heat flux conditions according to reliability distribution function. The results show the output power of TEG is increased but its life length is reduced with increasing temperature. With the ceramics plate, the sheet metal and the semiconductor structure working temperature as 486K, 453K and 450K, respectively, the TEG working life length is about 96999.4h while the TEG working life length is only 0.2h with the temperature of TEM structure as 943K, 864K and 857K, respectively. But, the power of TEM would be increased with increasing temperature as 0.0076W, 0.0475W and 0.0932W, respectively. The TEG is consisted of a large number of TEM and the power of TEG would be output for necessary. There is some option temperature for TEM working in reasonable condition. The TEG working life length is short in high temperature, while the TEG output power is less in low temperature.

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