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(RESEARCH ARTICLE)

Theoretical analysis of thermoelectric module

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Abstract

A thermoelectric generator was used to recover waste heat from a heat source, such as engine exhaust. The key elements of the thermoelectric generator are heat exchanger and thermoelectric module. Thermoelectric modules convert heat energy to electrical energy using the Seebeck effect. A temperature difference between the hot and cold sides of the thermoelectric module is required to generate electric power. A theoretical model was developed to predict thermoelectric current, voltage, and power output. A bismuth Telluride thermoelectric module was used for analysis. It was observed that the thermoelectric voltage increased with the external load resistance, and the thermoelectric power output increased at a certain load resistance and then decreased. Under the match load condition, the maximum thermoelectric power output was obtained.

Keywords: Bismuth Telluride module; External resistance load; Thermoelectric module; Thermoelectric power output

1. Introduction

An Engine exhaust carries 30 to 40% of the combustion heat and it is released in to the atmosphere as waste heat. If waste heat is recuperated, a significant amount of fuel may be stored [1]. Waste heat recuperation technology can be utilized to store energy [2]. If part of the unwanted heat energy is recuperated, energy performance can be enhanced, and automobiles can save energy and decrease global warming worldwide [3]. Waste heat restoration technology facilitates the regulation of engine temperature [4]. According to the exhaust temperature conditions, turbocharger, unique heat exchangers, bottoming cycles, and thermoelectric systems used for heat recovery [1, 5, 6]. Mechanical or electrical energy can be generated using high temperatures, and a low temperature can be utilized for water or area heating. Waste heat restoration techniques should be selected according to temperature conditions [7]. Engine producers have accelerated engine efficiency by enforcing exclusive strategies, such as superior gas/air mixing, turbocharging, and variable valve timing [8]. It's observed that only 5-6 % exhaust heat is transferred into electrical energy, it shows to save 10% fuel due to reduction in mechanical losses of alternator drive [9]. Fuel reduction depends on heat recovery technologies and the driving cycle [10]. The transformation of the difference in temperature to electric power or vice versa is known as the thermoelectric effect (TEE). Thermoelectric systems are small in shape, with no moving parts, no fluid for processing and are lightweight [11]. Thermoelectric systems have some limitations such as low efficiency and high cost, which restrict their put in medical, space and military applications [12, 13]. Thermoelectric generators are an alternative source for converting solar power into electric power, apart from photovoltaic technology [14]. Thermoelectric generators are also utilized in different types of wood stoves to produce electric power, light and power fans [15-17]. The thermoelectric properties should be known before using a thermoelectric module for waste heat recovery.

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This study focused on the theoretical analysis of a thermoelectric module. Engine exhaust was considered as the heat source and cold water was considered as the heat sink. Bismuth Telluride was used for the analysis. A theoretical model is used to predict the thermoelectric current, voltage, and power output.

2. Thermal Resistance Network

The waste heat from the engine exhaust (Q_H) is transferred in an upward direction through a thermocouple of the thermoelectric module and heat release (Q_C) at the heat sink. Part of the waste heat is transferred to electrical power (Q_P). The arrangement of the thermal resistance of the thermoelectric module (TEM) thermocouple is illustrated in Figure 1. All the thermal resistances were in series, except for the TEM in parallel. The following equations were used to determine all the thermal resistance.

Thermal resistance of grease:

$$R_{Grease} = \frac{L_{Grease}}{k_{Grease} A_{Grease}} \quad (1)$$

Thermal resistance of ceramic material:

$$R_{Ceramic} = \frac{L_{Ceramic}}{k_{Ceramic} A_{Ceramic}} \quad (2)$$

Thermal resistance of copper (Cu) material:

$$R_{Copper} = \frac{L_{Copper}}{k_{Copper} A_{Copper}} \quad (3)$$

Thermal resistance of solder:

$$R_{Solder} = \frac{L_{Solder}}{k_{Solder} A_{Solder}} \quad (4)$$

Thermal resistance of P-type thermoelectric element:

$$R_{P-type} = \frac{L_{P-type}}{k_{P-type} A_{P-type}} \quad (5)$$

Thermal resistance of N-type thermoelectric element:

$$R_{N-type} = \frac{L_{N-type}}{k_{N-type} A_{N-type}} \quad (6)$$

Where, $L_{Grease}, L_{Ceramic}, L_{Copper}, L_{Solder}, L_{P-type}, L_{N-type}$, are the thickness of grease, ceramic, copper, solder, P-type and N-type, respectively. $A_{Grease}, A_{Ceramic}, A_{Copper}, A_{Solder}, A_{P-type}, A_{N-type}$ are the heat transfer area of grease, ceramic, copper, solder, P-type and N-type, respectively. $k_{Grease}, k_{Ceramic}, k_{Copper}, k_{Solder}, k_{P-type}, k_{N-type}$ are the thermal conductivity of grease, ceramic, copper, solder, P-type and N-type, respectively.

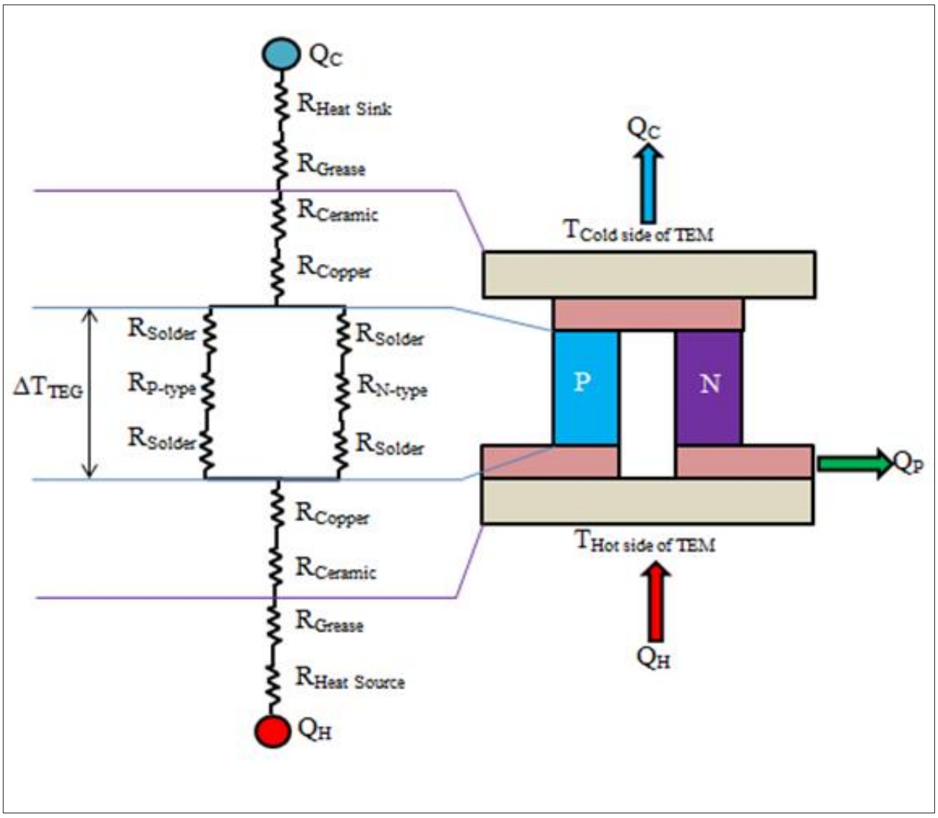

Figure 1 Thermal resistance network of a single thermoelectric couple of thermoelectric module

According to the thermal resistance network, the temperature difference between the cold side (T_c) and hot side (T_h) of the thermoelectric element (ΔT_{TEG}) was determined using the following equation. Based on the cold side and hot side temperatures of the TEM, the thermoelectric power generation of the element can be predicted.

$$\Delta T_{TEG} = \frac{[(R_{Solder} + R_{P-Type} + R_{Solder}) \parallel (R_{Solder} + R_{N-Type} + R_{Solder})] \times (T_h - T_c)}{2 \times (R_{Grease} + R_{Ceramic} + R_{Copper}) + [(R_{Solder} + R_{P-Type} + R_{Solder}) \parallel (R_{Solder} + R_{N-Type} + R_{Solder})]} \quad (7)$$

Table 1 Material properties of Bismuth Telluride (single thermoelectric elements) at 300K used in the analysis work [18]

Parameter (300 K)	**P-type element**	**N-type element**	**Thermal grease**	**Ceramic**	**Copper**	**Solder**
Seebeck coefficient (V/K)	0. 215x10^{-3}	-0. 212 x10^{-3}	NA	NA	NA	NA
Thermal conductivity (W/m K)	1.373	1.456	3	22	385	50
Contact area (M^2)	0.063x10^{-4}	0.063x10^{-4}	0.13x10^{-4}	0.13x10^{-3}	0.13x10^{-4}	0.063x10^{-3}
Thickness (m)	0.8x10^{-3}	0.8x10^{-3}	0.02x10^{-3}	0.8x10^{-3}	0.5x10^{-3}	0.05x10^{-3}

The thermal resistance of the solders and p-type thermoelectric elements are connected to another thermal resistance of the solders, and the n-type thermoelectric elements are parallel. Therefore, it is essential to determine the equivalent resistance for the same. The following equation was used to determine equivalent resistance.

$$R_{equivalent} = \frac{1}{\frac{1}{(R_{Solder} + R_{P-Type} + R_{Solder})} + \frac{1}{(R_{Solder} + R_{N-Type} + R_{Solder})}} \quad (8)$$

Perfect interfacing contacts of all elements are considered. The following equation shows the relationship between (ΔT_{TEG}) and (T_h- T_C).

$$\Delta T_{TEG} = 0.874(T_h - T_c) \quad (9)$$

All the above parameters are required to determine ΔT_{TEG}, as presented in Table 1,

3. Theoretical Analysis

When a temperature difference occurs between the cold and hot sides of a thermoelectric element, an electric potential is generated.

The thermoelectric generator performance is measured in terms of output power as follows [19]:

$$P = I^2 R_{Load} = \frac{(\Delta T_{TEG})^2 \times (\alpha_P - \alpha_N)^2 \times R_{Load}}{(R_{\text{int}} + R_{Load})^2} \quad (10)$$

Where, I indicates the thermoelectric current, R_{Load} is the external load resistance, α_N & α_P are the Seebeck coefficients of the N-type and P-type thermo element materials, respectively, and R_{int} is the internal resistance of the thermoelectric material.

The output power of a TEM is controlled by its characteristics, number of thermoelectric elements, dimensions, material properties, and temperature difference between the cold and hot sides of the TEM.

The conversion efficiency is determined as:

$$\eta = \frac{P}{Q_h} = \frac{I^2 R_{Load}}{(\alpha_P - \alpha_N) I T_h - 0.5(I^2 R_{\text{int}}) + K(\Delta T_{TEG})} \quad (11)$$

Where, Q_h indicates the heat from the exhaust supplied to the TEM, and K is the thermal conductance of the TEG.

According to impedance-matching theory, the maximum output power of a TEM is generated when the internal resistance matches with the external load resistance.

The maximum power output would be:

$$P_{\max} = \frac{(\Delta T_{TEG})^2 \times (\alpha_P - \alpha_N)^2}{(4R_{\text{int}})} \quad (12)$$

The output power of TEM can be predicted.

3.1. Material Properties of TEP1-1264-1.5 and Dimensions

In this work, sixteen numbers of bismuth telluride (TEP1-1264-1.5) thermoelectric modules was used; each module consisted of 127 thermoelectric couples. The thermoelectric properties of the thermoelectric generator are listed in Table 2. The specifications (description) of the thermoelectric modules are listed in Table 3. All of the above properties of the thermoelectric material are used to determine the thermoelectric current, voltage, output power, and conversion efficiency. In the present work, the above mathematical model was used to predict the thermoelectric current, voltage, output power, and transformation efficiency.

Inputs are required to determine output power and transformation efficiency of thermoelectric generator. Table 4 listed all parameters for the following case.

Temperature at hot side (T_h) = 42.6°C

Temperature at cold side (T_h) = 30.6°C

Temperature difference (ΔT_{TEG})= 0.874 ×12 = 10.488°C

Internal resistance (R_{int}) = 2.8 × 16 = 44.8 Ω

Seebeck coefficient (αp-αn) = 0.867664 V/K

Conductance (K) = 39.178 K/W

Table 2 Material properties of Bismuth Telluride (sixteen thermoelectric modules) at 300K used in the analysis work

Parameter (at 300 K)	**P-type element**	**N-type element**	**Thermal grease**	**Ceramic**	**Copper**	**Solder**
Seebeck coefficient (V/K)	0.43688	-0.430784	NA	NA	NA	NA
Thermal conductivity (W/m K)	1.373	1.456	3	22	385	50
Contact area (m^2)	0.012801	0.0128016	0.000013	0.026416	0.026416	0.0128016
Thickness (m)	0.0008	0.0008	0.00002	0.0008	0.0005	0.00005
Calculated						
Calculated Thermal resistance	0.0455150	0.0429204	0.0002523	0.0013765	0.00004916	0.00007811

Table 3 Description of the thermoelectric module (TEM)

TEM	**Model Dimension**	**Parameters**	**Value**
TEP1-1264-1.5	40 x 40 x 3.5 mm	Temperature (˚C) (Hot Side)	300
		Temperature (˚C) (Cold Side)	30
		Open Circuit Voltage (V)	9.40
		Resistance (ohms) (Matched Load)	2.80
		Output voltage (V) (Matched Load)	4.70
		Output current (A) (Matched Load)	1.56
		Output power (W) (Matched Load)	7.30

Table 4 Theoretical result of the first case of the work

Sr. No.	Resistance (Ω)	Voltage (Volt)	Current (Amp)	Power output (W)	Efficiency (%)
1	0	0.000	0.203	0.000	0.000
2	5	0.914	0.183	0.167	0.040
3	10	1.661	0.166	0.276	0.066
4	15	2.283	0.152	0.347	0.084
5	20	2.809	0.140	0.394	0.095
6	25	3.259	0.130	0.425	0.102
7	30	3.650	0.122	0.444	0.107
8	35	3.991	0.114	0.455	0.110
9	40	4.292	0.107	0.461	0.111
10	45	4.560	0.101	0.462	0.112
11	50	4.800	0.096	0.461	0.111
12	60	5.210	0.087	0.452	0.109
13	70	5.549	0.079	0.440	0.106
14	80	5.833	0.073	0.425	0.103
15	90	6.076	0.068	0.410	0.099
16	100	6.285	0.063	0.395	0.096

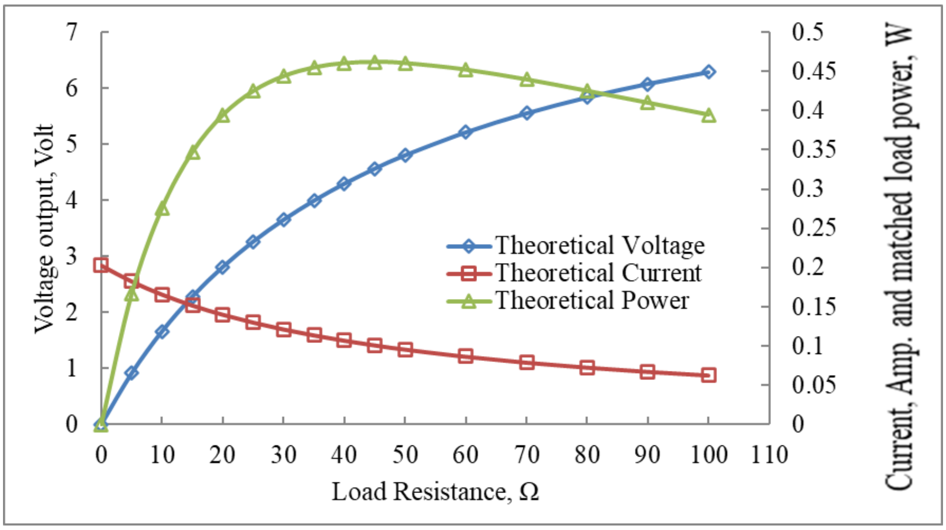

Figure 2 Theoretical current, voltage and power out variation with external load resistance

Figure 2 shows the current, voltage, and output power of the thermoelectric module as a function of the external load resistance. The thermoelectric voltage increase with the load resistance, but the thermoelectric current gradually decreased with the external load resistance. The thermoelectric power increased with external load resistance up to a certain level and then decreased. The theoretical efficiency increased with increasing external load resistance up to a certain level, and then decreased with increasing external load resistance, as shown in Figure 3.

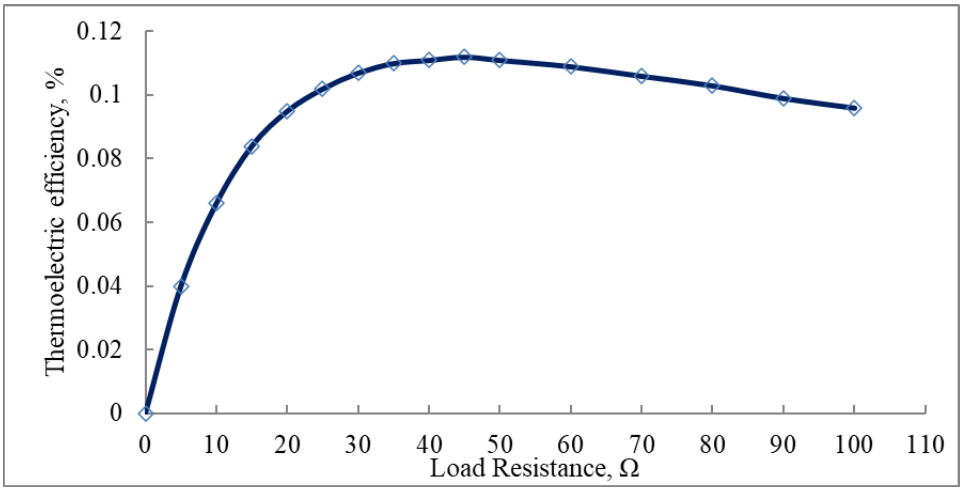

Figure 3 Theoretical thermoelectric efficiency variations with external load resistance

4. Conclusion

A thermoelectric model of module was developed. Specifications of the thermoelectric module are required to develop a theoretical model of the thermoelectric system. The cold and hot side temperatures of the thermoelectric module were sufficient to predict the output power and conversion efficiency with the help of theoretical thermoelectric models. In the future, this study will be used to design a thermoelectric generator for power generation.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could influence the work reported in this study.

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