Review on Design and Analytical Model of Thermoelectric Generator

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Abstract:

Despite all advances in the miniaturization of Microsystems which depend on a central power source or bulky batteries with limited lifetime. Growing fields like autonomous Microsystems or wearable electronics urgently look for micro scale power generators. One possible solution is to convert waste heat into electrical power with TEG.

Thermoelectric generator is a useful and environment friendly device with the advent of semiconductor materials the efficiency of a TEG can even be an alternative for the conventional heat engines.

To fabricate thermoelectric generators, one must design the structure of the TEG. This study investigated the role of the dimensions of TEG, including the length, and cross-sectional area of the thermo elements to evaluate the power and efficiency, The governing equations were derived from the Seebeck effect and Peltier effect. We calculated the thermoelectric power generated by the TEG and efficiency. The thermoelectric simulation produced design guidelines for high-performance TEG.

Keywords: Thermoelectric generator, Seebeck Co-efficient, Power factor, p-type, n-type.

Introduction:-

For the sustainable development of humankind and to stop climate change as outlined in the Kyoto Protocol, the use of conventional energy sources such as fossil fuels will have to be limited in the very near future.

As one such alternative, thermoelectric energy has many favorable characteristics light weight, small scale, and low manufacturing cost [1]. Thermoelectric generators have been used in military, aerospace, instrument, industrial and commercial products, as a power-generation device for specific purposes. Many researchers have been concerned about the physical properties of thermoelectric materials and the manufacturing technique of thermoelectric modules [2]. In addition to the improvement of the thermoelectric materials and modules, the system analysis (and optimization) of a thermoelectric generator is equally important in designing high-performance thermoelectric-generator. Especially, the capacity of Peltier and Seebeck effect to dispense with the moving parts in the realm of energy transformation from heat to electricity and vice versa is more appealing in such devices. With the advent of semiconductor materials the efficiency of a thermoelectric generator can even be an alternative for the conventional heat engines [3]. So, the mathematical modeling of a simple thermoelectric generator can also replace the elaborate task of simulating an actual complex power plant, heat engine or refrigerator.

A TEG produces a voltage when there is a temperature difference between the hot-side and cold-side of TEG. Thermoelectric effect includes Seebeck effect, Peltier effect and Thomson effect, it also accompanies with other effects, such as Joulean effect and Fourier effect. Thermoelectric generation is a technology for directly converting-thermal energy into electrical energy, it has no moving parts, is compact, quiet, highly reliable and environmentally friendly. Because of these merits, it is presently becoming a noticeable research direction [4].

Thermo Electric Generator Concept:-

In 1822 the German Scientist Seebeck discovered that a loop of two dissimilar metals developed an e.m.f. when the two junctions were kept at different temperatures. This effect has long been used in thermo-couples to measure temperatures. This phenomenon offers one method of producing electrical energy directly from the heat of combustion.

Principle of Working:-

Thermo-electric generator is a device which converts heat energy (thermal energy) into electrical energy through semi-conductor or conductor.

Consider a loop made of two dissimilar metal as shown in fig. and two junctions are maintained at T_h (hot junction temp.) and T_c (cold junction temp.) then the voltage developed in the open loop is given by

$$V = \alpha_{S_{1-2}} \Delta T \quad (1)$$

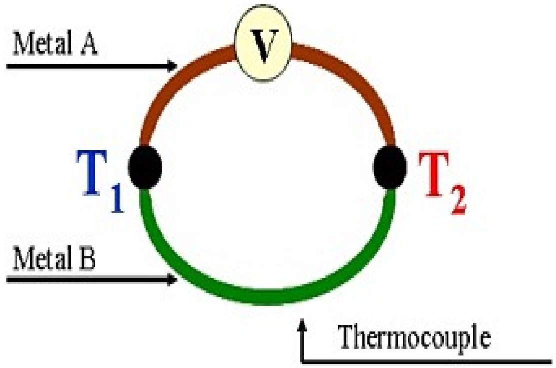
Where α_{S1-2} is the seebeck coefficient. In most cases $\alpha_{S_{1-2}}$ is depend on temperature, so that for larger temperature difference it is more accurate to express equation (1) in the form

$$V = \int_{T_1}^{T_2} \alpha s_{1-2} dT \quad (2)$$

Therefore, we have to select the combination of the materials for the given temperature difference (T_h - T_c) so the value of V becomes maximum.

$$\alpha_{S_{1-2}} = \lim_{\Delta T \to 0} \frac{\Delta V}{\Delta T} = \frac{dV}{dT} \quad (3)$$

The Seebeck coefficient depends upon the choice of the materials and cannot be attributed to either material above. It has unit of volt per degree.



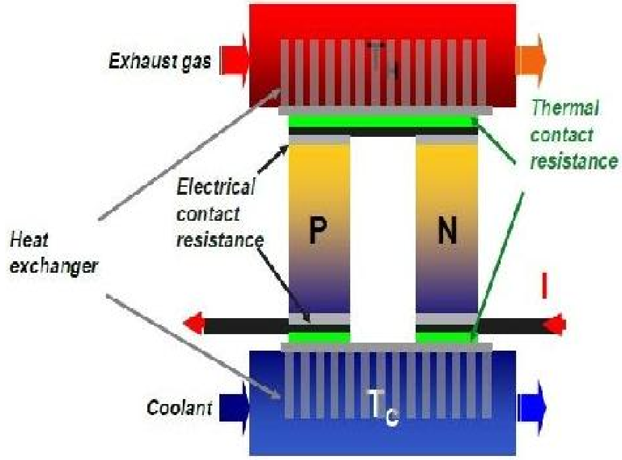
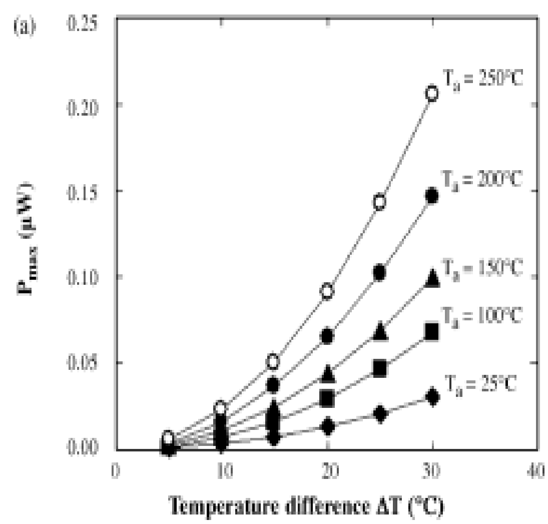


Fig.1: Thermo-electric converter

Literature review:-

M.Takashiri(2007) et al. has been done Bismuth–telluride-based alloy thin film thermoelectric generator was fabricated by a flash evaporation method. The maximum output power of the thin film thermoelectric generator in this study is still not enough to apply as a power source for microelectronic devices. And for improving the performance of the generator they used hydrogen annealing process [5].



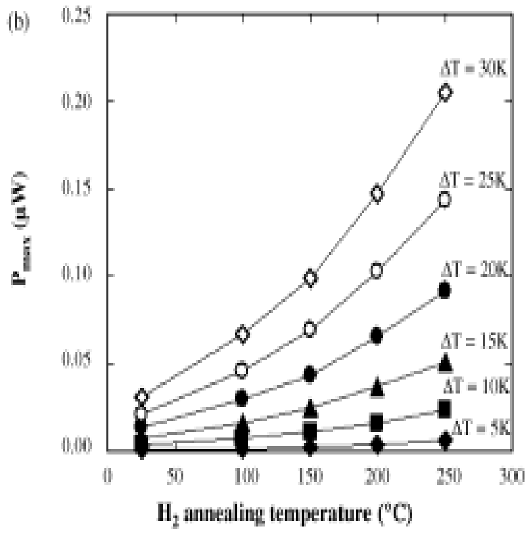


Fig. 2: Maximum output power vs temperature difference and annealing temperature[5]

Bongkyun Jang et al. represented (2011) using finite element analysis he concluded, as the substrate gets thicker the thermoelectric performance deteriorates due to thermal loss from the substrate. The thermo elements have an optimal length with the highest power High efficiency is obtained when the length of the thermo elements is large [6].

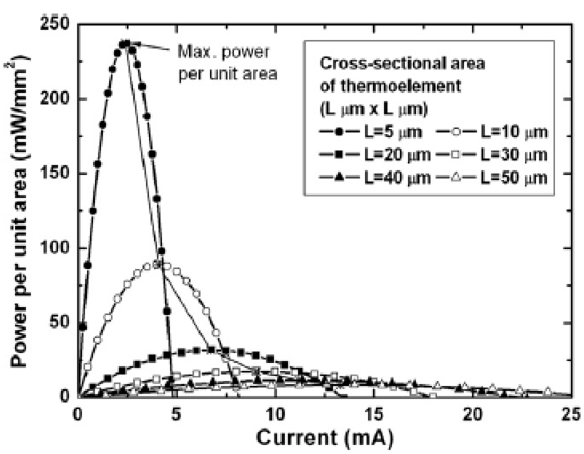


Fig. 4: Maximum power per unit area obtained in thermoelectric unit with thermo element of various cross sectional areas [6]

P. Phaga et al. (2012) has been investigated low cost thermoelectric generator (LCTEG) and high performance to reduce costs of production. The thermoelectric power generation composed of small n-type (n-CaMnO3) and p-type (p-Ca3Co4O9) of 31 couples/ in^2 and the use of thin copper plate and silver paint as electrodes. It was found that the mean voltage is ~121.7 mV, current is ~0.0121mA; power is ~1.47 μW [7].

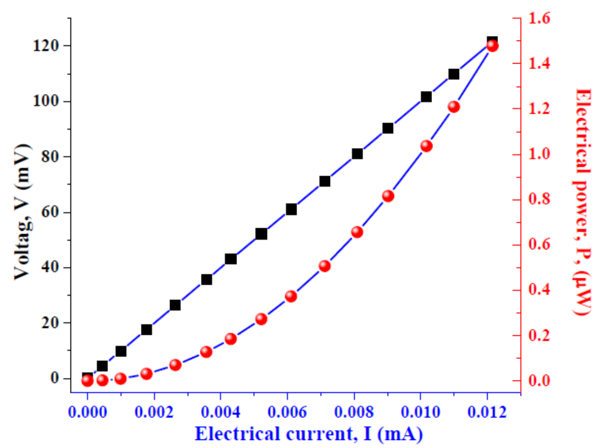


Fig. 5: The relationship of I-V curve and electrical power of TEG at different temperature[7]

Thermoelectric Materials:-

Lead telluride (P_bT_e), Bismuth telluride (C specific heat capacity (J/kg K) $B_{i2}T_{e3}$), Bismuch sulfide ($B_{i2}S_3$), Antimony telluride ($S_{b2}T_{e3}$), Tin telluride (S_nT_e), indium arsenide, germanium telluride (G_eT_e), cesium sulfide (C_eS), zinc antimonied (Z_nS_b)

Lead telluride (P_bT_e), a compound of lead and tellurium, containing small amounts of either bismuth (n-type) or sodium (p-type) has been commonly used in recent times for thermoelectric converters.

Table: Figure of merit for thermoelectric materials.

Materials	**Z(°*K*$^{-1}$)**
1. Bismuth telluride	4×10^{-8}
2. Lead telluride	1.5×10^{-3}
3. Germanium telluride	1.5×10^{-3}
4. Zinc antimonied	1.5×10^{-3}
5. Cesium sulfide	1.0×10^{-3}

Conceptual Design:-

The structure of a typical one TE module TEG is shown schematically in Fig. 6, it consists of a TE module, a heat source and a heat sink. A TE module consists of number of P-N thermocouples, conductive tabs, and two ceramic substrates. When the temperature of the heat source and the heat sink cause the temperature difference between the hot-side and cold side of thermocouples, thermoelectric effects will occur. Therefore, a current I will flow through an external load resistance rL because of the temperature difference.

Nomenclature:-

C	specific heat capacity (J/kg K)
T	temperature (ºC)
αs	Seebeck coefficient (V/K)
ρ	specific resistivity(ohm-cm)
K	thermal conductance
K_H	thermal conductance of high temperature side
K_L	thermal conductance of low temperature side
n	type of semiconductor material
p	type of semiconductor material
Q_H	heat transfer rate from the high temperature
Q_L	heat transfer rate from the low temperature sink
R	total electrical resistance
ΔT	applied temperature gap across a module
I	Load current (A)
R_L	electric load (X)
U	overall heat transfer coefficient
Z	figure of merit
λ	thermal conductivity (W/mK)
σ	electrical conductivity S/m
P opt	optimum output power (W)
η opt	optimum efficiency of TEG
P max	maximum power output(W)
η max	total efficiency of thermoelectric generator
L	length of the leg of a thermoelectric device
A	area of thermoelectric device

Mathematical modeling:-

The following assumptions are made to simplify the complex problem of modeling:
a) All the TE modules of the TEG are the same model, which means that they have the same inherent parameters (m, a, K, r and re).
b) The heat conduction between thermocouples is ignored, as the heat conduction from hot-side to cold-side within the thermocouples as axial heat conduction will be dominant.
c) The Seebeck coefficient, thermal conductivity and resistivity of semiconductor thermocouples are constants.
d) On the assumption that Seebeck coefficient remains unchanged, the influence of Thomson effect is not considered.

There are thermo electric modules in the TEG shown in Fig. 6. To a TE module, let m be the number of thermocouples, a (α_s) be the Seebeck coefficient of a thermocouple, K be the thermal conductance of all thermocouples, r be the internal resistance of a TE module, r_e be the contact resistance of a TE module which including the contact resistance between thermocouples and conductive tabs, the internal resistance of conductive tabs.

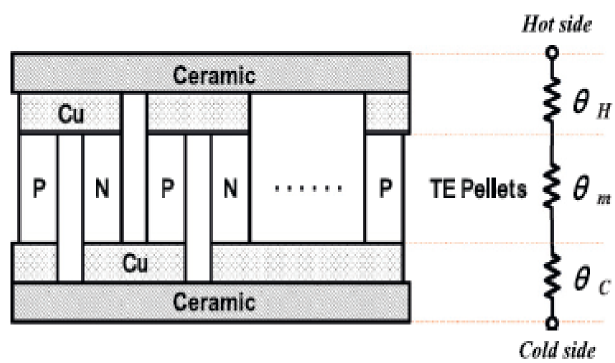
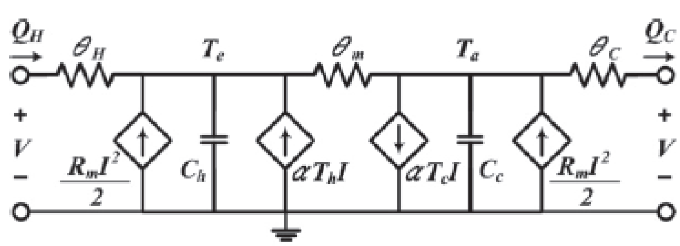


Fig. 6: Structure and Thermal Resistor Network of Thermoelectric Module



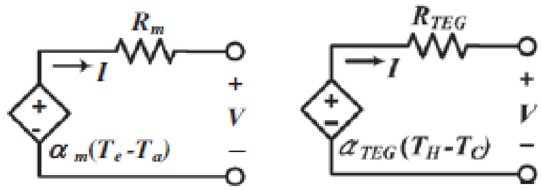


Fig. 7: Schematic Diagram of a TEG

It can be seen form K_h and K_c consist of many parts of thermal conductance and thermal resistance, so K_h and K_c can be expressed as eq.3

$$\frac{1}{K_h} = \frac{1}{K_1} + \frac{1}{K_2} + R_1 + R_2 + R_h \quad (4)$$

$$\frac{1}{K_c} = \frac{1}{K_1} + \frac{1}{K_2} + R_1 + R_2 + R_3 + R_c \quad (5)$$

It is assumed that every TE module in TEG works on different conditions, such as different heat source temperature, and different heat sink temperature. Let Q_h (W) present the heat that absorbed and Q_c (W) present the heat that released from its heat source and to its heat sink per unit time.

According to Fourier's law, Q_h and Q_c can be expressed as

$$Qh = Kh(T_h - T_1)$$
$$Qc = Kc(T_2 - T_c) \quad (6)$$

In addition, Q_h consists of three parts of heat, Peltier heat on the hot-side of thermocouples, Joule heat generated by internal resistance of the TE module as the current flow through the TEG circuit, and conduction heat from the hot-side to the cold-side of the thermocouples [8,9]. So Q_h, Q_c can also be expressed as

$$Q_h = m\alpha t_1 I - \frac{1}{2} I^2 (r + r_e) + K(T_1 - T_2) \quad (7)$$

$$Q_c = m\alpha t_1 I - \frac{1}{2} I^2 (r + r_e) + K(T_1 - T_2) \quad (8)$$

Let the current flowing through the load be I, according to Kirchhoff's current law, in a parallel circuit the total current is equal to the sum of the currents in each individual branch, the current I can be expressed as

$$I = I_1 + I_2 + \ldots + I_n = \sum_{i=1}^{n} I \quad (9)$$

Let the load resistance of the TEG be rL, the output power of the TEG be P (W), and thus P can be expressed as

$$P = I^2 r_L \quad (10)$$

In addition, according to the law of energy conservation, P can also be expressed as

$$P = \sum_{i=1}^{n} (Q_h - Q_c) \quad (11)$$

Combining Equations (7)-(11), we get

$$(\sum_{i=1}^{n} I)^2 r_L = \sum_{i=1}^{n} [m\alpha (T_1 - T_2) I - I^2 r] \quad (12)$$

Combining Equations (6), and (12), we will get

$$\Delta T = (T_1 - T_2) = \frac{1}{\frac{m\alpha B}{r + r_e + nr_L} + A} (T_h - T_c)$$

$$I = \frac{m\alpha \Delta T}{r + re + nr} = \frac{m\alpha (T_h - T_c)}{m^2 \alpha^2 B + A(r + r_e + nr_L)} \quad (13)$$

Where,

$$A = 1 + \frac{K}{K_h} + \frac{K}{K_c}$$

$$B = \frac{T_h}{K_c} + \frac{T_c}{K_h} \quad (14)$$

Therefore, the total current of the TEG is

$$I = \sum_{i=1}^{n} \frac{m\alpha (T_h - T_c)}{m^2 \alpha^2 B + A(r + r_e + nr_L)} \quad (15)$$

The output power of the TEG is

$$P = \left[\sum_{i=1}^{n} \frac{m\alpha (T_h - T_c)}{m^2 \alpha^2 B + A(r + re + nr_L)} \right]^2 r_L \quad (16)$$

When the source and sink temperature of each TE module are known, and the thermal contact resistances are measured, let $\frac{dp}{dr_L}=0$, the maximum output power and match load of the TEG can be got. However, as the Eq. (16) is very complicated, Equation (15), (16) can be simplified as

$$P_{\max}=\frac{nm^2\alpha^2(T_h-T_c)^2}{4m^2\alpha^2AB+4(r+r_e)A^2} \qquad (17)$$

$$I=\frac{\frac{m\alpha}{A}(T_h-T_c)}{\frac{m^2\alpha^2B+A(r+r_e)}{A}+r_L} \qquad (18)$$

Conclusion:-

An analytical model of TEG will be developed based on thermodynamic theory, semiconductor thermoelectric theory, and law of conservation of energy, the equations of output power and current of thermoelectric generator (TEG).

From above various papers studied result shown that the efficiency and power generated by various methods of thermoelectric generator (TEG) is very low.

According to the analysis the output power per area is independent of the number of the thermo legs and of their cross-sectional area. Instead it depends just on the ratio of the cross sectional areas of insulation and of the length of the thermo legs. The power shows a maximum for a certain thermocouple length depending on the other parameters. so, to improve the performance of thermoelectric generator (TEG) by modifying the parameters and design methodology.

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