

Thermoelectric Energy Harvesting

Chris Gould, Staffordshire University, Stoke-on-Trent, United Kingdom, c.a.gould@staffs.ac.uk

Abstract

Thermoelectricity can be used to generate electrical power from temperature gradients or differences in naturally occurring geothermal heat and rocks, or from waste heat in man-made equipment and industrial processes. Thermoelectric energy harvesting systems are finding commercial applications to replace or recharge batteries in low power electronic systems. This chapter provides the fundamental thermoelectric theory related to power generation, including the theoretical analysis and numerical calculations required to calculate the thermoelectric efficiency and electrical power generated when a single thermoelectric couple, and a 127 couple thermoelectric module, are subject to different temperature gradients. A thermoelectric energy harvesting system, incorporating a low power boost converter and DC to DC converter, coupled with electrical energy storage in supercapacitors, is presented and enables a thermoelectric energy harvesting system to provide sufficient electrical power to operate low power electronic components and systems. The short-term challenge for thermoelectric energy harvesting is to become a cost effective and practical solution to replace batteries, and to be scaled to provide sufficient power to operate electrical rotating machines such as low power motors and pumps. The long-term challenge is to improve the efficiency, power output, and cost of thermoelectric modules and energy harvesting systems, and to develop from low power to low-to-medium power applications.

Keywords: Thermoelectric, Seebeck, temperature difference, temperature gradient, thermal power generation

1. Introduction

Energy harvesting is an ideal platform to foster research and the commercial application of thermoelectric power generation. The use of naturally occurring temperature gradients or differences found in geothermal heat and rocks, or by man-made waste heat in machinery and industrial processes, can be used to generate electrical power by thermoelectricity. The concept of using thermoelectricity to generate electrical power has been discussed for some time, and is considered to be an environmentally friendly and renewable technology, although thermoelectricity is often overlooked in discussions surrounding renewable energy sources, partly due to the relatively low levels of electrical power generated from a thermoelectric module, which is typically in the milli watt to watt range, and the low conversion efficiency of between 5% to 10% [1]. However, with the addition of power electronics, coupled with electrical energy storage in electric double layer capacitors, also known as supercapacitors, the instantaneous electrical power output from a thermoelectric power generation system can be increased to a useful level, and can output sufficient electrical power to operate low power electronic systems, recharge or replace batteries in many applications. Furthermore, thermoelectricity can be used in applications where other energy harvesting techniques could not be used, i.e. where light is not available for photovoltaic power generation, or wind for electromagnetic generation, or can be used in combination with other energy harvesting technologies in order to enhance a systems overall performance. The technology is not limited to low power applications, with an on-going focus and research into thermoelectric power generation from waste heat in the automotive market, and is extensively used to provide power to deep-space spacecraft.

The technology has several advantages when used for power generation; thermoelectric modules can function in harsh environments; are relatively small in size and weight; there are no moving parts and very low, if any, maintenance requirements; electrically quiet in operation; do not import dust or other particles; can be oriented in any direction; and the same module can be used for power generation, cooling and heating. The main disadvantage of thermoelectricity is the relatively low conversion efficiency and thermoelectric figure of merit Z_T .

Thermoelectricity has undergone stages of significant interest, research and development, along with periods of inactivity and decline. The scientific principle and potential application of thermoelectric power generation has been known for some time and can be described as the generation of electrical power, via the Seebeck effect, when two dissimilar conducting materials are connected together at one

end and subject to a temperature gradient or temperature difference. The fundamental scientific discoveries applicable to thermoelectricity were discovered in the 1800's, with the most important for power generation being the Seebeck effect discovered by Thomas Seebeck in 1821. It should be noted that thermoelectricity can also be used for cooling and heating applications, where a source of DC power is applied to a thermoelectric couple or module's input terminals, resulting in one side of the couple or module reducing in temperature and the other side increasing in temperature and acting as a heat pump. This cooling and heating effect is primarily due to the Peltier effect, discovered in 1834 by Joseph Peltier, and to a lesser extent the Thomson effect in 1855 by William Thomson, later known as Lord Kelvin. Recognition should also be made to Alessandro Volta as an early pioneer in thermoelectric research. The technology developed slowly until the 1930's, when rapid improvements in all areas of thermoelectricity occurred and by the mid 1960's, practical thermoelectric devices emerged for niche applications in aerospace cooling and spacecraft power. Progress in efficiency improvement slowed and research peaked in 1963, followed by a steep decline in activity that was to continue for nearly three decades [2]. However, around 1990 there was renewed interest in thermoelectricity due to a combination of factors, notably environmental concerns regarding refrigerant fluids, alternative refrigeration and interest in cooling electronics [3]. Contemporary interest in the technology is driven by an increasing awareness of the effect of climate change on the planet's environment, a renewed requirement for long-life electrical power sources and energy harvesting technologies, and the increasing miniaturization of electronic circuits and sensors [4]. In recent years, interest has grown in the use of ambient energy sources to power low power electronic systems, with thermoelectricity being one of the most promising and applicable energy harvesting technologies for commercial exploitation.

2. Background thermoelectric theory

This section will present the fundamental thermoelectric theory related to thermoelectric power generation for a single thermoelectric couple, and a 127 couple thermoelectric module.

2.1 Standard thermoelectric couple and module construction

A single thermoelectric couple is constructed from two 'pellets' of semiconductor material usually made from Bismuth Telluride (Bi_2Te_3), as this material has been found to show the most pronounced thermoelectric effects around room temperature. One of these pellets is doped with acceptor impurity to create a P-type pellet, the other is doped with donor impurity to produce an N-type pellet. The two pellets are physically linked together on one side, usually with a small strip of copper, and mounted between two ceramic outer plates that provide electrical isolation and structural integrity. A single thermoelectric couple, as shown in Figure 1, is generally of limited practical use, as the rate of useful power generated due to the Seebeck effect is very small. Practical thermoelectric modules are constructed with several of these thermoelectric couples connected electrically in series and thermally in parallel, with modules typically containing a minimum of three thermoelectric couples, as shown in Figure 2, rising to one hundred and twenty seven couples for larger devices [5].

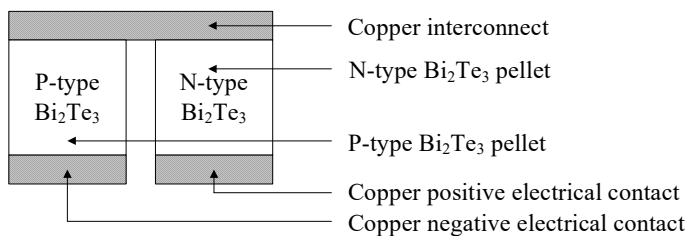


Figure 1 - A single thermoelectric couple

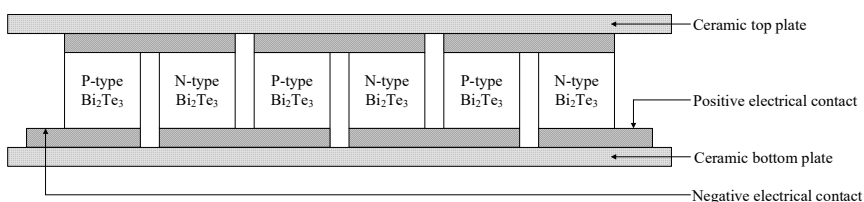


Figure 2 - A three couple thermoelectric module

2.2 The principle of thermoelectric power generation for a single thermoelectric couple

If a temperature difference is maintained between two sides of a thermoelectric couple, thermal energy will move through the p-type and n-type pellets. As these pellets are electrically conductive, charge carriers are transported by this heat. This movement of heat and charge carriers creates an electrical voltage called the Seebeck voltage. If a resistive load is connected across the thermoelectric couple's output terminals, current will flow in the load and an electrical voltage will be generated at the load [6]. A schematic diagram of a single thermoelectric couple, configured for thermoelectric power generation, with the output terminals of the couple connected to a volt meter in order to measure the open-circuit voltage V_{oc} is shown in Figure 3(a), and connected to a resistive load R_L in Figure 3(b).

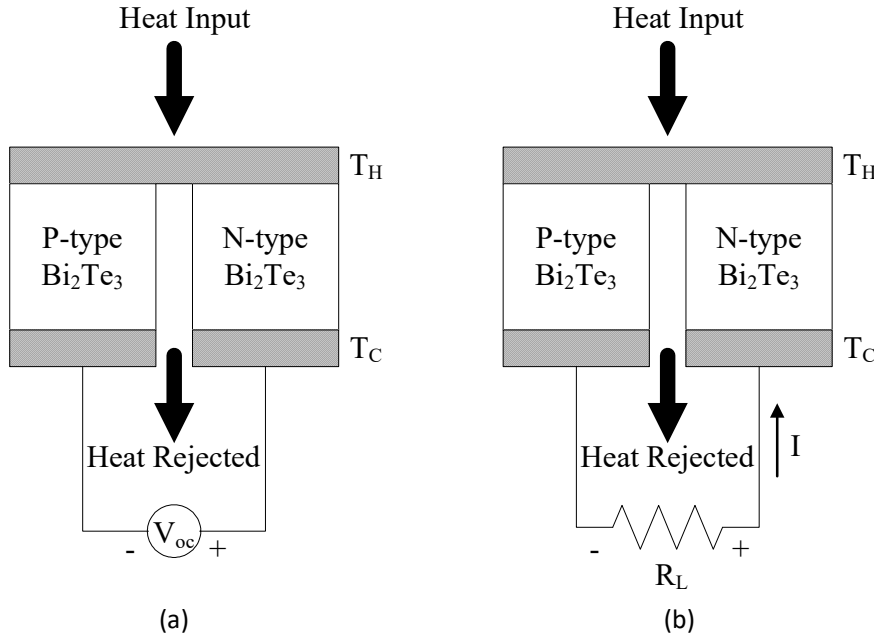


Figure 3 - A single thermoelectric couple configured as a thermoelectric generator with a volt meter measuring the open-circuit voltage V_{oc} (a) and in (b) with a load resistor R_L connected across the couple's output terminals [7]

2.2.1 Calculating the thermoelectric couple open-circuit voltage V_{oc}

According to [8], if we consider the thermoelectric couple in Fig. 3 (a), and assume that no other heat arrives at the cold side T_c other than through the two thermoelectric legs, the thermoelectric couple open-circuit voltage V_{oc} can be found by:

$$V_{oc} = (\alpha_p - \alpha_n)(T_h - T_c) \quad \text{measured in volts} \quad (1)$$

where α_p and α_n is the Seebeck coefficient of the p-type and n-type pellets of the thermoelectric couple respectively, and may be found quoted in manufacturer literature or obtained by practical measurement. Typical values for Bi_2Te_3 thermoelectric couples are α_p of around 230×10^{-6} V/K and α_n of around -195×10^{-6} V/K [9]. T_h is the surface temperature of the hot side of the thermoelectric couple, and T_c is the surface temperature of the cold side of the thermoelectric couple, measured in Kelvin.

2.2.2 Calculating the resistance R_p and R_n of the thermoelectric couple pellets

The electrical resistivity ρ of each pellet can be found and/or measured, with a typical resistivity for p-type Bi_2Te_3 thermoelectric pellets of around 1.75×10^{-3} Ohms-centimetre, and for n-type Bi_2Te_3 pellets of around 1.35×10^{-3} Ohms-centimetre [10]. The resistance R_p of the p-type pellet can then be found by:

$$R_p = \frac{L_p \rho_p}{A_p} \quad \text{measured in Ohms} \quad (2)$$

where ρ_p is the electrical resistivity of the pellet in Ohms-cm, L_p is the length of the pellet in cm, and A_p is the cross-sectional area of the pellet in cm^2 found by:

$$A_p = width \times depth \quad \text{measured in } cm^2 \quad (3)$$

Similarly, the resistance of the n-type pellet R_n can be found by:

$$R_n = \frac{L_n \rho_n}{A_n} \quad \text{measured in Ohms} \quad (4)$$

2.2.3 The thermoelectric couple resistance R_c

The thermoelectric couple resistance R_c , ignoring the resistance of the copper interconnects, is the addition of the resistance of the two thermoelectric pellets:

$$R_c = R_p + R_n \quad \text{measured in Ohms} \quad (5)$$

The resistance of the copper interconnects is typically in the micro ohm region, and compared with the resistance of the Bi_2Te_3 thermoelectric pellets, which tends to be in the milli ohm region, is significantly smaller in value and hence can be considered as negligible.

2.2.4 Calculating the thermal conductivity K_p and K_n of the thermoelectric couple thermoelements (legs)

The thermal conductivity λ of each pellet can be found and/or measured, with a typical conductivity for a p-type Bi_2Te_3 thermoelectric pellet of around $1.2 \times 10^{-3} W/cm K$, and for an n-type Bi_2Te_3 pellet of $1.4 \times 10^{-3} W/cm K$ [10]. The thermal conductivity K_p of the p-type thermoelement can be found by:

$$K_p = \frac{\lambda_p A_p}{L_p} \quad \text{measured in watts cm kelvin} \quad (6)$$

where λ_p is the thermal conductivity of the pellet in Watts/cm Kelvin, L_p is the length of the pellet in cm, and A_p is the cross-sectional area of the pellet in cm^2 . Similarly, the thermal conductivity of the n-type pellet K_n can be found by:

$$K_n = \frac{\lambda_n A_n}{L_n} \quad \text{measured in watts cm kelvin} \quad (7)$$

It should be noted that the electrical resistivity ρ is the reciprocal of the electrical conductivity σ and can also be found using:

$$\sigma = \frac{I \times L}{V \times A} \quad \text{measured in siemens} \quad (8)$$

where I is the current through a constant cross-sectional area A and length L when a voltage V is applied [8].

2.2.5 Calculating the current I when a load resistor R_L is connected across the thermoelectric couple output terminals

If a load resistance R_L is now connected across the output terminals of the thermoelectric couple, as shown in Figure 3 (b), the current I can be expressed as:

$$I = \frac{V}{R_T} \quad \text{measured in amperes} \quad (9)$$

where V is the closed-circuit voltage, and R_T is the total resistance of the thermoelectric couple and the load. It is possible to find R_T using:

$$R_T = R_p + R_n + R_L \quad \text{measured in Ohms} \quad (10)$$

Using (Eq. (1)) and Eq. ((10)), the current I can be found by:

$$I = \frac{(\alpha_p - \alpha_n)(T_h - T_c)}{R_p + R_n + R_L} \quad \text{measured in amperes} \quad (11)$$

2.2.6 The load current I_L and the voltage generated at the load V_L

As the load resistor R_L is connected across the output terminals of the couple, the load current I_L is the same as the circuit current I , and the voltage generated at the load V_L can be found by:

$$V_L = I_L \times R_L \quad \text{measured in volts} \quad (12)$$

2.2.7 The electrical power generated at the load P_L

The electrical power generated at the load P_L can be found using:

$$P_L = I^2 R_L \quad \text{measured in watts} \quad (13)$$

If we substitute (Eq. (11)) into (Eq. (13)), we obtain:

$$P_L = \left\{ \frac{(\alpha_p - \alpha_n)(T_h - T_c)}{R_p + R_n + R_L} \right\}^2 R_L \quad \text{measured in watts} \quad (14)$$

Alternatively, the electrical power generated at the load can be found by:

$$P_L = V_L \times I_L \quad \text{measured in watts} \quad (15)$$

In electrical and electronic engineering, the maximum power transfer between the generator and the load normally occurs when the load resistance is equal to the generator resistance, and if we consider the thermoelectric couple as an ideal model, with no heat lost through thermal radiation or conduction, and ignoring any effect of contact resistances, the maximum efficiency of a thermoelectric generator will not exceed 50%. It should be noted that if the load resistance is increased away from the value that gives rise to maximum power transfer, the power output of the thermoelectric generator will be reduced [8].

2.2.8 Calculating the thermoelectric couple efficiency

The efficiency η of a thermoelectric couple can be found by:

$$\eta = \frac{\text{Energy supplied to the load}}{\text{Heat energy absorbed at the hot junction}} \quad (16)$$

The electrical power supplied to the load is P_L , and we now need to find the heat energy absorbed at the hot junction. A proportion of the heat that is absorbed at the hot junction from the heat source T_h is used to balance the Peltier cooling effect in the thermoelectric couple, and an opposing flow of heat occurs due to the thermal conduction of the thermoelectric legs, and by Joule heating within the device. The cooling effect at the source Q_{source} can be found by:

$$Q_{source} = (\alpha_p - \alpha_n) I_L T_h \quad \text{measured in watts} \quad (17)$$

The opposing heat by conduction in the thermoelectric legs (or pellets) can be found by:

$$Q_{legs} = (T_h - T_c)(K_p + K_n) \quad \text{measured in watts} \quad (18)$$

where K_p and K_n are the thermal conductance of the p-type and n-type thermoelectric legs respectively. The cooling effect is opposed by Joule heating Q_j within the thermoelectric legs, found by:

$$Q_j = \left(\frac{I^2 (R_p + R_n)}{2} \right) \quad \text{measured in watts} \quad (19)$$

According to [8], it can be shown that half of the Joule heating passes to the sink T_c and half to the source T_h , with each half equal to (Eq. (19)). The expression for the heat energy absorbed at the hot junction, which is the same as the cooling power at the hot side of the thermoelectric couple Q_h can now be found by:

$$Q_h = (\alpha_p - \alpha_n) I T_h - (T_c - T_h)(K_p + K_n) - \frac{I^2 (R_p + R_n)}{2} \quad \text{measured in watts} \quad (20)$$

Hence, the efficiency of the thermoelectric couple η can now be found by (Eq. (16)), and written as:

$$\eta = \frac{P_L}{Q_h} \quad (21)$$

Substituting Q_h from (Eq. (20)) and P_L from (Eq. (14)) into (Eq. (21)), we obtain:

$$\eta = \frac{\left\{ \frac{(\alpha_p - \alpha_n)(T_h - T_c)}{R_p + R_n + R_L} \right\}^2 R_L}{(\alpha_p - \alpha_n) / T_h - (T_c - T_h) (K_p + K_n) - \frac{I^2 (R_p + R_n)}{2}} \quad (22)$$

In thermoelectricity, efficiency is expressed as the dimensionless figure-of-merit Z , or more commonly, expressed as a function of the temperature over which the device is operated Z_T . The thermoelectric figure-of-merit Z describes the thermoelectric efficiency of a thermoelectric couple for a given pair of p-type and n-type thermoelectric materials, and is normally shown as:

$$Z = \frac{\alpha^2}{\lambda \rho} \quad (23)$$

where α is the Seebeck coefficient of the thermoelectric couple, λ is the thermal conductivity, and ρ is the couple's electrical resistivity. In the context of this discussion, the Seebeck coefficient of the couple is equal to $(\alpha_p - \alpha_n)$, the thermal conductivity λ is $(K_p + K_n)$, and the electrical resistivity ρ is equal to $(R_p + R_n)$, therefore (Eq. (23)) can be rewritten as:

$$Z = \frac{(\alpha_p - \alpha_n)^2}{(K_p + K_n)(R_p + R_n)} \quad (24)$$

The thermoelectric figure-of-merit Z is commonly used to optimize the performance of materials used in the manufacture of thermoelectric couples. However, when stating the thermoelectric efficiency, it is more common to express it as a function of the temperature over which the device is operated, referred to as Z_T , which can be found by using (Eq. (23)) at a specific temperature, and is normally written as:

$$Z_T = \frac{\alpha^2 \sigma}{\lambda} \quad (25)$$

where α is the Seebeck coefficient, σ is the electrical conductivity, and λ is the thermal conductivity of the couple at a specific operating temperature.

2.3 Thermoelectric module power generation

If we now consider a thermoelectric module that contains several thermoelectric couples connected electrically in series, and thermally in parallel, as shown in Figure 2, a small amount of electrical power, typically in the milli-watt range (mW), can be generated from a thermoelectric module if a temperature difference is maintained between two sides of the module. Normally, one side of the module is attached to a heat source and is referred to as the 'hot' side or T_H . The other side of the module is typically attached to a heat sink and is called the 'cold' side or T_C . The heat sink is used to create a temperature difference between the hot and cold sides of the module. If a resistive load R_L is connected across the module's output terminals, electrical power will be generated at the load when a temperature difference exists between the hot and cold sides of the module due to the Seebeck effect. A schematic diagram of a thermoelectric module, operating as a thermoelectric power generator, is shown in Figure 4.

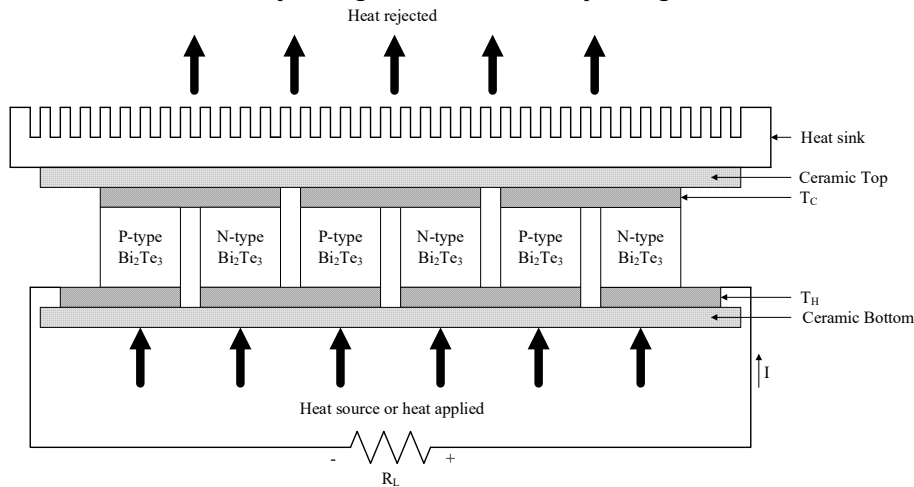


Figure 4 - A thermoelectric module configured for thermoelectric power generation

According to [11] the thermoelectric module open-circuit voltage V_{oc} can be obtained by:

$$V_{oc} = \alpha_m(T_h - T_c) \quad \text{measured in volts} \quad (26)$$

where α_m is the thermoelectric module's average Seebeck coefficient in volts per kelvin, and may be found quoted in manufacturers literature. If a load resistance R_L is now connected across the output terminals of the thermoelectric module, the current I can be found by:

$$I = \frac{V}{R_m + R_L} \quad \text{measured in amperes} \quad (27)$$

where V is the closed-circuit voltage and R_m is the thermoelectric module's average resistance in Ohms. As the Seebeck coefficient and module resistance are temperature dependent, their values should be calculated at the average or mean module temperature T_m given by:

$$T_m = \frac{T_h + T_c}{2} \quad \text{measured in kelvin} \quad (28)$$

The voltage at the load V_L can be found by:

$$V_L = I_L \times R_L \quad \text{measured in volts} \quad (29)$$

where the current at the load I_L is equal to the circuit current I . The electrical power generated by the module at the load can then be found by:

$$P_L = I_L^2 \times R_L \quad \text{measured in watts} \quad (30)$$

or by using:

$$P_L = V_L \times I_L \quad \text{measured in watts} \quad (31)$$

The efficiency η of the thermoelectric module can be found by:

$$\eta = \frac{P_L}{Q_h} \quad (32)$$

The cooling power at the hot side of the thermoelectric module Q_h can be found by:

$$Q_h = (\alpha_m)IT_h - (T_c - T_h)(K_m) - \frac{I^2(R_m)}{2} \quad \text{measured in watts} \quad (33)$$

The efficiency η of the thermoelectric module can now be found by:

$$\eta = \frac{\left\{ \frac{(\alpha_m)(T_m)}{R_m + R_L} \right\}^2 R_L}{(\alpha_m)IT_h - (T_c - T_h)(K_m) - \frac{I^2(R_m)}{2}} \quad (34)$$

The thermoelectric figure-of-merit Z_T can be found using:

$$Z_T = \frac{\alpha_m^2 \sigma_m}{\lambda_m} \quad (35)$$

where α_m is the module's average Seebeck coefficient, σ_m is the average electrical conductivity, and λ_m is the module average thermal conductivity, at a specific operating temperature.

2.4 A numerical analysis of a thermoelectric power generation module

If we consider a thermoelectric module, [12] have published some general material properties data for a 127 thermoelectric couple module. For the purpose of this analysis, we will use a hot side temperature T_H of 400 Kelvin, and a cold side temperature T_C of 300 Kelvin. The Seebeck coefficient and module resistance is temperature dependent, hence, their values should be calculated at the average module temperature T_m given by:

$$T_m = \frac{T_h + T_c}{2} \quad \text{measured in kelvin} \quad (36)$$

$$T_m = \frac{400 + 300}{2}$$

$$T_m = 350 \text{ Kelvin}$$

According to [12], with an average module temperature of 350 Kelvin, the module thermoelectric parameters are; a Seebeck coefficient α_m of 0.05544 Volts/Kelvin; a module resistance R_M of 4.6491 Ohms; and a thermal conductivity K_M of 0.4422 Watts/Kelvin.

2.4.1 The thermoelectric module open-circuit voltage V_{oc}

The thermoelectric module open-circuit output voltage V_{oc} can be found by using (Eq. (26)) as:

$$V_{oc} = \alpha_m(T_h - T_c) = 0.05544 \times (400 - 300)$$
$$V_{oc} = 5.544 \text{ V}$$

2.4.2 Connecting a load resistor R_L across the output terminals of the module

If we set the load resistance R_L to the value of the internal resistance of the thermoelectric module R_M of 4.6491 Ohms, the load resistance becomes:

$$R_L = 4.6491 \Omega$$

2.4.3 The closed-circuit voltage V

The open-circuit voltage V_{oc} was calculated in 2.4.1, and in this case, when a load resistor R_L is connected across the output terminals of the thermoelectric module, the closed-circuit voltage V is:

$$V = 5.544 \text{ V}$$

2.4.4 The circuit current I

With a load resistance R_L connected across the output terminals of the module, the current I can be found by (Eq. (27)) as:

$$I = \frac{V}{R_M + R_L} = \frac{5.544}{4.6491 + 4.6491} = \frac{5.544}{9.2982}$$
$$I = 0.596 \text{ A}$$

2.4.5 The load current I_L and the voltage generated at the load V_L

The load current I_L is the same value as the circuit current I , hence:

$$I_L = 0.596 \text{ A}$$

The voltage generated at the load can be found by (Eq. (29)) as:

$$V_L = I_L \times R_L = 0.596 \times 4.6491$$
$$V_L = 2.7710 \text{ V}$$

2.4.6 The electrical power generated at the load P_L

The electrical power generated by the module at the load can now be found by (Eq. (30)) as:

$$P_L = I_L^2 \times R_L = 0.596^2 \times 4.6491$$
$$P_L = 1.6514 \text{ W}$$

or by using (Eq. (31)) as:

$$P_L = V_L \times I_L = 2.7710 \times 0.596$$
$$P_L = 1.6515 \text{ W}$$

2.4.7 The efficiency of the thermoelectric module η

The cooling power at the hot side of the thermoelectric couple Q_h can be found by (Eq. (33)) as:

$$Q_h = (\alpha_m)IT_h - (T_c - T_h)(K_m) - \frac{I^2(R_m)}{2}$$

$$Q_h = ((0.05544) \times 0.596 \times 400) - ((300 - 400)(0.4422)) - \frac{0.596^2(4.6491)}{2}$$

$$Q_h = 13.2169 - (-100 \times (0.4422)) - \frac{0.3552 \times (4.6491)}{2}$$

$$Q_h = 13.2169 + 44.22 - 0.8257$$

$$Q_h = 56.62 \text{ W}$$

Hence, the efficiency of the thermoelectric module η can now be found by (Eq. (32)) as:

$$\eta = \frac{P_L}{Q_h} = \frac{1.6515}{56.62}$$

$$\eta = 0.0292$$

$$\text{or } \eta = 0.0292 \times 100 = 2.92\%$$

2.4.8 Numerical analysis of the 127 couple thermoelectric module configured for thermoelectric power generation with a temperature difference ΔT varied between 0 and 100 Kelvin

A summary of the performance characteristics of the 127 couple thermoelectric module obtained by theoretical calculation is shown in Table 1. The temperature difference ΔT , which is equal to $T_H - T_C$, has been varied between 0 and 100 Kelvin, in 10 Kelvin steps, and the results calculated. The thermoelectric module's power generated at the load P_L , voltage V_L , current I_L , and efficiency η , is shown in Figure 5, Figure 6, and Figure 7 respectively. The results demonstrate the theoretical electrical power generated by a 127 couple thermoelectric module is typically in the mW to watt range when the module is subject to a temperature difference from 10 Kelvin to 100 Kelvin.

T_H K	T_C K	T_m K	ΔT K	α_m V/K	K_m W/K	R_m Ω	R_L Ω	V_{oc} V	V_L V	I A	P_L W	Q_h W	Efficiency η %
300	300	300	0	0.05343	0.35	3.72	3.72	0.00	0.00	0.00	0.00	0.00	0.00
310	300	305	10	0.05343	0.35	3.72	3.72	0.53	0.27	0.07	0.02	4.65	0.41
320	300	310	20	0.05418	0.36	3.91	3.91	1.08	0.54	0.14	0.08	9.55	0.79
330	300	315	30	0.05418	0.36	3.91	3.91	1.63	0.81	0.21	0.17	14.40	1.17
340	300	320	40	0.05477	0.37	4.10	4.10	2.19	1.10	0.27	0.29	19.81	1.48
350	300	325	50	0.05477	0.37	4.10	4.10	2.74	1.37	0.33	0.46	24.90	1.84
360	300	330	60	0.05519	0.39	4.28	4.28	3.31	1.66	0.39	0.64	30.98	2.07
370	300	335	70	0.05519	0.39	4.28	4.28	3.86	1.93	0.45	0.87	36.33	2.40
380	300	340	80	0.05542	0.42	4.47	4.47	4.43	2.22	0.50	1.10	43.19	2.55
390	300	345	90	0.05542	0.42	4.47	4.47	4.99	2.49	0.56	1.39	48.82	2.85
400	300	350	100	0.05544	0.44	4.65	4.65	5.54	2.77	0.60	1.65	56.62	2.92

Table 1 – Summary of performance characteristics of a 127 couple thermoelectric module obtained by theoretical calculation

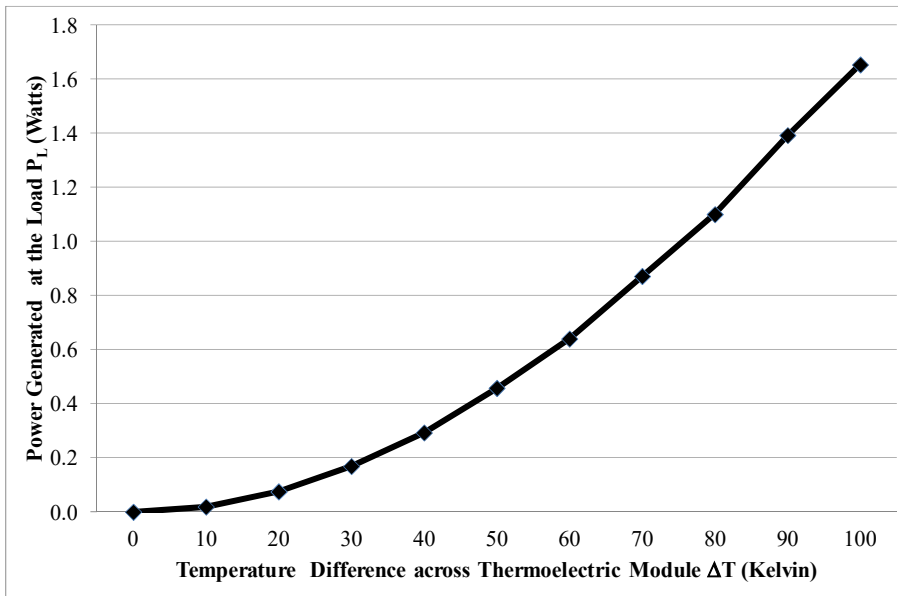


Figure 5 - Power generated at the load P_L with a temperature difference ΔT between 0 and 100 Kelvin (theoretical results)

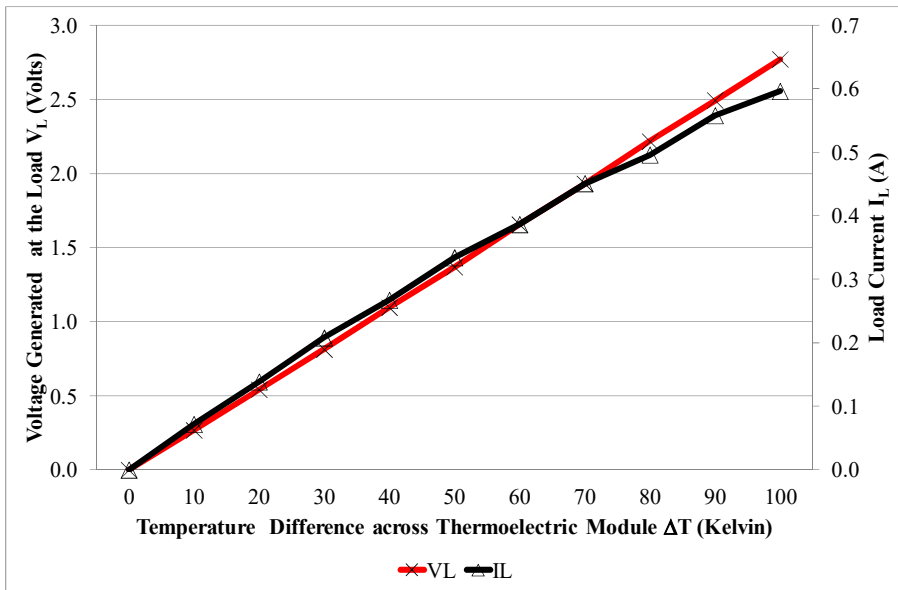


Figure 6 - Voltage V_L and Current I_L generated at the load with a temperature difference ΔT between 0 and 100 Kelvin (theoretical results)

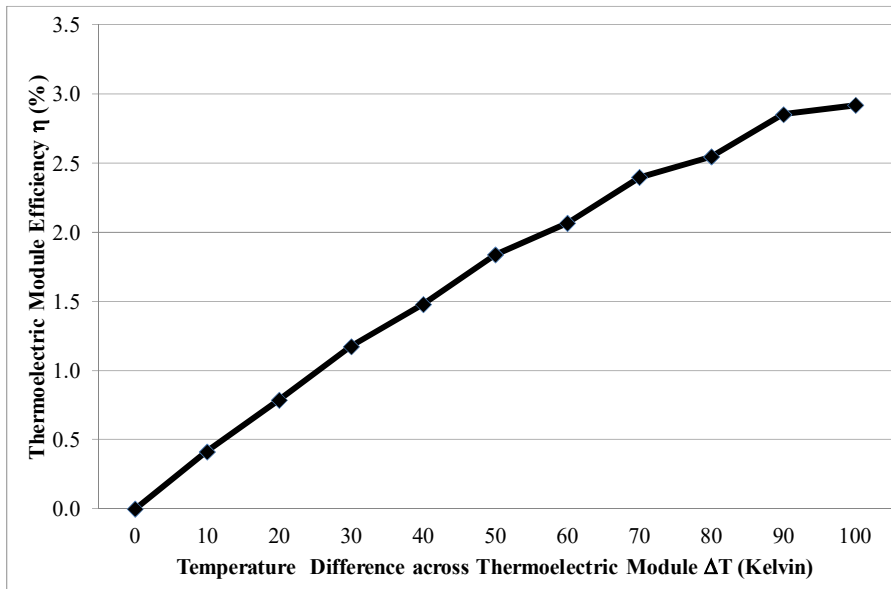


Figure 7 - Thermoelectric module efficiency with a temperature difference ΔT between 0 and 100 Kelvin (theoretical results)

3. Thermoelectric power generation and energy harvesting system

Thermoelectric power generation systems have typically needed to have a very high temperature gradient across the thermoelectric module(s) in order to achieve a useful electrical power output. This limitation has been a barrier to the successful application of this technology for power generation, and limited the technologies use to mainly niche applications, for example, in deep-space spacecraft power. However, with parallel developments in the area of electrical energy storage in supercapacitors, and low power DC to DC converters and boost converters, it is possible to develop a thermoelectric energy harvesting system that will operate from very low temperature gradients of around one Kelvin and be able to output useful power levels. This was previously very difficult to achieve and would have required several thermoelectric modules to be connected electrically in series, and thermally in parallel, increasing the overall system weight, size, and cost, and would only achieve relatively small levels of power generation unless a significant temperature gradient could be achieved across the modules.

The thermoelectric output voltage generated by a standard thermoelectric module can be boosted to a useful and stable level by using a low power boost converter and DC to DC converter. If the electrical power output from the DC to DC converter is then accumulated and stored for future use in a supercapacitor, it is possible to increase the potential output current of the system, and hence the overall power output of the thermoelectric energy harvesting system. A simplified block diagram of a thermoelectric energy harvesting system is shown in Figure 8, highlighting the five main stages of the system. The energy stored in the supercapacitor can be accumulated over time and released to the load when required. In some applications, it may be advantageous to use a voltage regulator after the supercapacitor in order to maintain a stable output voltage to the load.

In general, the duty cycle of the electrical load is a critical factor in determining the design of a thermoelectric energy harvesting system. As highlighted earlier, the output power of a single thermoelectric module is often too low to power other electrical and electronic components directly unless a significant temperature difference or gradient is available, or several thermoelectric modules are connected together electrically in series and thermally in parallel. The use of temporary electrical storage in supercapacitors leads to a focus on the duty cycle of the load, as it is necessary to ensure the capacitor can be recharged before the load becomes active to ensure repeatable and reliable operation.

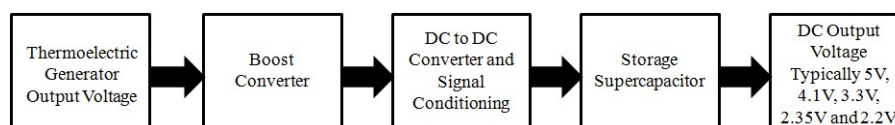


Figure 8 – Simplified thermoelectric energy harvesting block diagram [14]

3.1 Thermoelectric energy harvesting circuit

A thermoelectric energy harvesting circuit to power an electronic load is shown in Figure 9, and is based around a Linear Technology LTC3108 step-up DC to DC converter. The thermoelectric module output voltage is in the mV range when the module is subject to a small temperature difference, and is boosted to a useful level by the LTC3108 step-up converter. The LTC3108 uses a boost converter, in the form of an external step-up transformer, an internal MOSFET and associated circuitry within the DC to DC converter, to increase the voltage from the thermoelectric module. Within the converter, a MOSFET switch is used to form a resonant step-up oscillator using an external 1:100 turn transformer and a small coupling capacitor $C3$ of around $330\mu\text{F}$. The frequency of oscillation is determined by the inductance of the transformer secondary winding and is typically in the range of 10kHz to 100kHz. The AC voltage that is developed on the secondary winding of the transformer is boosted and rectified using an external charge pump capacitor $C1$ of 1nF and the internal rectifiers within the DC to DC converter. The DC to DC converter itself is powered via the internal VAUX circuitry, from the input voltage supplied by the thermoelectric module, and when the VAUX supply exceeds 2.5V, the main output of the DC to DC converter V_{out} becomes operational and can be programmed by the user to one of four regulated voltages of; 2.35V; 3.3V; 4.1V; and 5V [13]. The converter operates at very low input voltages of 20mV, which can be achieved when a one kelvin or higher temperature difference exists between the 'hot' and 'cold' sides of the thermoelectric module. Dependent on the input power received from the thermoelectric module, the DC to DC converter output V_{out} will be charged over time up to its regulated voltage [13], and in this case, the 1F supercapacitor will charge up to 5V at a maximum current of 4.5mA.

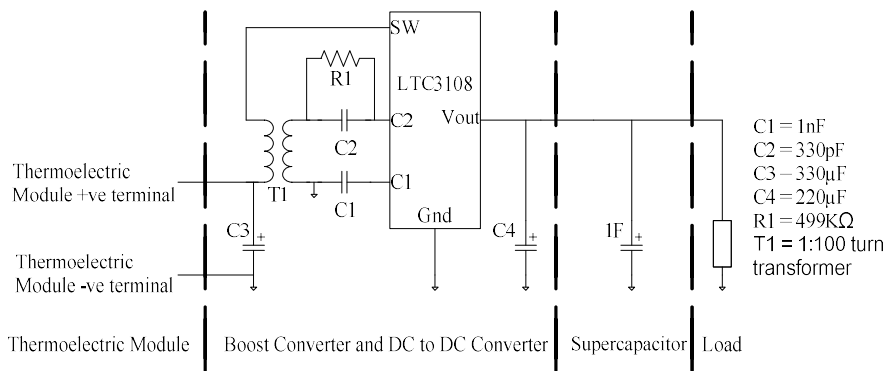


Figure 9 - Thermoelectric energy harvesting circuit [14]

3.2 Evaluation of the thermoelectric energy harvesting system

For the purpose of evaluation, a Melcor CP1.4-127-045L thermoelectric module and HX8-202-FM heat sink is connected for power generation, with a hot side temperature T_H of 323 Kelvin, and a temperature difference between both sides of the module ΔT of 9 Kelvin, the thermoelectric module's open-circuit voltage is 310 mV. An LTC3108EDE step-up DC to DC converter evaluation board, configured to output 5V on the V_{out} pin, was connected to the thermoelectric module output terminals as shown in Figure 9. When the thermoelectric module is connected to the LTC3108 converter, the module's output voltage and current is 116mV at 30mA. The boost converter and DC to DC converter increases the thermoelectric output voltage, and supplies a stable voltage of 5V at 0.4mA to the 1F storage supercapacitor, charging the supercapacitor. The 1F supercapacitor reaches maximum charge after approximately three hours [14]. Increasing the temperature difference across the thermoelectric module, and therefore increasing the thermoelectric module's output power, would have the effect of increasing the output current of the DC to DC converter, up to a maximum of 4mA, reducing the capacitor charge time significantly.

If an electrical load is connected across the supercapacitor output terminals, the supercapacitor will discharge and supply electrical power to the load. For evaluation purposes, a number of different electrical loads have been tested, and successfully operate from the electrical power delivered from the supercapacitor during discharge including; a piezoelectric buzzer; light emitting diode (LED); humidity sensor; pressure sensor; low power microcontroller; DC motor; and a miniature electronic water pump.

The piezoelectric buzzer, LED, humidity sensor, and pressure sensor can be powered for a considerable amount of time before the 1F capacitor becomes discharged. For example, a maplin electronic KU58 piezoelectric buzzer operates between 3V and 12V with a maximum input current of 2.38mA at 5V, and successfully operates above 3V for 18 minutes, and is still audible for in excess of one

and a half hours when connected to the 1F supercapacitor. The miniature electronic water pump, DC motor, and low power microcontroller operate successfully from the 1F supercapacitor, however, the evaluation system would benefit from scaling the storage 1F capacitor appropriately to enable stable operation for significant periods of time. Notwithstanding this, and focusing on the miniature electronic water pump, an RS components 702-6894 electronic micropump that has an operating voltage of 1.2V to 6V was connected to the output terminals of the of the 1F supercapacitor. The pump inlet and outlet tubes were connected together to form a 10 cm length of plastic tube, filled with water, and was seen to successfully pump this water around the tube for approximately 1 minute and 30 seconds. Once the water pump minimum supply voltage of 1.2V was reached during the first 35 seconds of the supercapacitor's discharge, the pump continued to operate, although at a reduced flow rate than observed earlier. The water pump draws a maximum input current of 72mA at 5V and can achieve a maximum flow rate of 150ml per minute [14].

In general, a device with a; low input voltage; low current consumption; and a wide operating input voltage range; can be powered for a considerable amount of time directly from the supercapacitor. It should be noted that the performance of the two test circuits can be improved, with the addition of a resistor in series with the load in order to limit the current drawn by the load, or by using a voltage regulator after the supercapacitor, with an appropriate output capability, which would supply a stable output voltage to the load [14].

4. Discussion

The electrical output power obtained from a standard thermoelectric module is relatively small and in the mW range unless a significant temperature gradient can be achieved across two sides of the module, however, in common with other energy harvesting technologies, if the output voltage of the thermoelectric module is boosted to a useful level, i.e. to common battery supply voltages of; 5V; 3.3V; 1.5V etc.; by using low power boost converters and DC to DC converters, and electrical energy storage in supercapacitors, practical thermoelectric energy harvesting systems can be realized which can output sufficient electrical power to operate low power electrical and electronic systems. This approach leads to a focus on the electrical load's duty cycle. Systems that rely on boost conversion and energy storage require the storage capacitor to be recharged in periods of load inactivity to enable continuous operation over an extended period of time. If the electrical load requires continuous power to operate, and the output power of the thermoelectric module is too low to power the load directly, the storage supercapacitor will eventually discharge completely and be unable to continuously power the load. However, in many applications the load does not need to be continuously powered – electronic sensors, microcontrollers, and RF networks often only need to make periodic readings, processing, and transmission cycles, and can be put into a low power 'sleep' mode when not in operation, drawing only a low quiescent current until 'waking-up' and drawing full current, allowing the supercapacitor time to recharge to a fully charged state. Applications where the electrical load is powered intermittently have become a focus for implementing low power thermoelectric energy harvesting systems.

The contemporary focus on low power energy harvesting systems will enable new thermoelectric applications to emerge and be realized. Thermoelectricity is commercially successful, having previously found applications in power generation for deep-space spacecraft power, military, and other niche applications. Recent focus has enabled thermoelectricity to replace or recharge batteries in low power electronic systems.

The short-term challenge for thermoelectric energy harvesting is to become a cost effective and practical solution to replace batteries in mainstream applications where access to temperature gradients or differences is available. Commercial success is often found in niche applications where there is a definite need and advantage, as the direct comparison with standard battery powered systems can highlight disadvantages of cost, size, weight, and complexity. However, as high volume thermoelectric applications emerge and are realized, the direct comparison with batteries will improve. Furthermore, with appropriate scaling and development, electrical rotating machines such as low power motors and pumps can be powered by a thermoelectric energy harvesting system, opening new applications and industries for exploitation.

The long-term challenge is to improve the efficiency and output power of thermoelectric modules, to develop new thermoelectric materials and module fabrication technologies, to reduce the cost of thermoelectric modules and energy harvesting systems, and to develop thermoelectric energy harvesting systems from low power to low-to-medium power applications.

Conclusion(s)

Thermoelectric energy harvesting systems can be implemented to generate sufficient electrical power from naturally occurring or man-made heat sources to provide power to low power electrical and electronic components and systems. The duty cycle of the electrical load is, in general, a critical factor in determining the feasibility of implementation as, without the addition of power electronics and electrical energy storage, the output power of a single thermoelectric module is often too low to power other electrical and electronic components directly unless a significant temperature difference or gradient is available, or several thermoelectric modules are connected together electrically in series and thermally in parallel. To overcome this limitation, energy harvesting systems typically employ a low power boost converter and DC to DC converter to increase the thermoelectric module's output voltage to a useful level, i.e. 5V, 3.3V, or 1.5V, and use a supercapacitor for temporary electrical energy storage and to provide power to an electrical load. The use of temporary storage in supercapacitors leads to a focus on the duty cycle of the load, as it is necessary to ensure the capacitor can be recharged before the load becomes active again to ensure repeatable and reliable operation. Successful applications have tended to be where there is a distinct need and advantage for implementation, and by replacing or recharging a battery in remote locations which are difficult to maintain and service. The short-term challenge for thermoelectric energy harvesting is to become a cost effective and practical solution to replace batteries in mainstream applications where access to temperature gradients or differences is available, and to be scaled to provide sufficient electrical power, and for the required duration, to enable electrical rotating machines such as low power motors and pumps to operate. The long-term challenge is to improve the efficiency and output power of thermoelectric modules, to develop new thermoelectric materials and fabrication technologies, to reduce the cost of thermoelectric modules and energy harvesting systems, and to develop thermoelectric energy harvesting systems from low power to low-to-medium power applications.

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