# UNIVERSITAT JAUME I

## ESCOLA SUPERIOR DE TECNOLOGIA I CIÈNCIES EXPERIMENTALS

## GRADO EN INGENIERÍA EN TECNOLOGÍAS INDUSTRIALES

# *SMALL SCALE ELECTRICITY GENERATION FROM WASTE-HEAT ENERGY FOR DEVELOPING COUNTRIES*

**TRABAJO FIN DE GRADO**

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# Abstract

More than half of the Sub-Saharan African population have limited or no access to electricity. Sub-Saharan Africa suffers from an almost non-existent power grid and where there is a grid there are many failing and outdated power plants. Many incentives have been made through off-grid solar panel technology and renewable technology, but it has proven to be too costly and complex for the local population. However, one option that is regularly overlooked is the thermoelectricity generation.

Thermoelectric generators (TEGs) convert the thermal energy flowing through them into DC electrical energy with a conversion of typically 5%. Nonetheless, they can be successfully employed to recover energy from waste heat of cooking stoves. Thermoelectric devices could rectify many of the characteristics associated with the African energy crisis providing electricity that permits the satisfaction of basic needs: light, phones and other electronic devices.

The performance of TEGs, subject to thermal and electrical effects, can vary considerably depending on the operating conditions; therefore the first part of this project involves the characterisation of their performance in an experimental rig designed in Trinity College. The analysis of this characterisation could maximise the power generated by the TEG and increase the overall efficiency of the system.

The second part of this project presents the design, construction and evaluation of a low-cost thermoelectric generator prototype that could use heat from cook stoves to generate small amounts of off-grid electricity.

# Acknowledgement

The completion of this project could not have been accomplish without the advice, support and direction from those around me.

I would like to thank Dr. Tony Robinson for his help throughout the duration of the project. He gave my valuable advice and ideas while letting me able to work autonomously.

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As my project is a continuation of the work conducted in 2013-2014, I would like to acknowledge previous PhD students. Their existing designs and construction of the rig gave me a good base to start my project.

Finally, I would like to convey my sincere gratitude for the continuous support from my fellow colleagues Gephane Filin, Maxime Anchisi and Samuel Martel, as well as all my family and friends, over the course of this project.

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# Chapter 1: Introduction

## 1.1. Project motivation

There is a general consensus that access to reliable and clean energy services to the population is critical to achieving sustainable development. Even still, the World Health Organization estimates that over 20% of the global population (~1.4 billion people) lack access to electricity. Furthermore, 40% of the global population (~2.7 billion people) rely on the traditional use of biomass cooking (1) (2) . Evidently there is still much work to do with regard to energy access for emerging countries, where there are literally billions of people living without access to vital energy services.

This situation is particularly prevalent in sub-Saharan Africa (SSA), where 69% of people lacked access to electricity (1). Families that survive with only basic lighting (candles, simple lamps and fires) lose opportunities for educational and income-generating activities outside of daylight hours. Further to this, the penetration of mobile telephony in SSA has been increasing steadily over the past several years. Mobile phones will surely play a vital role in the development of emerging countries and these too will require access to electricity.

*Figure 1: The Darkness of the African continent in comparison to Europe and India* (3)

This project details the development of a thermoelectric generator capable of delivering small amounts of off-grid electricity by using a small portion of heat from biomass-fuelled stoves commonly in use in the developing world, in particular in southern Africa. The device operates on the thermoelectric principle whereby small amounts of electricity can be produced in response to a temperature difference across a thermoelectric generator, or TEG.

Thermoelectric generators would allow families from the developing world to have access to electricity at an appropriate cost. Furthermore, they have the ability to be secured in the home (so difficult to steal) and can be manufactured and maintained close to the end users.

The first part of the project involved studying the operation and characterization of thermoelectric modules. The second part of the study focus on the development of a low-cost thermoelectric generator system that could use heat from stoves to generate enough electricity for lighting and phone charging in the developing world.

The specific objectives of the study are to:

- Analyse the characteristics of thermoelectric modules
- Testing a commercial thermoelectric module to compare experimental data with theoretical models commonly used in thermoelectric generators.
- Design a thermoelectric generator. That involves the design of an appropriate heat collecting and dissipating system to achieve the desired electrical energy.
- Integrate the thermoelectric module in a simple circuit that will facilitate DC-DC conversion.
- Test the generator system with an infrared heating element as heat source to simulate the cooking stove scenario.

The final product of this research will be a functional, power producing TEG to serve as a demonstration prototype.

## 1.2. Review of existing thermoelectric generators

With the increasing importance of the problems of climate change and in efforts to reduce $CO_2$ production the search for renewable energy sources has seen an increasing interest in the application of thermoelectric modules. Thermoelectric modules are capable of converting a temperature gradient into electricity or vice versa, and with improvements in the technology it is becoming possible to incorporate them in a growing range of applications. Thermoelectric generators (TEGs) in particular are useful for their ability to recover low-grade waste heat, which is available in huge amounts from power stations, internal combustion engines and other heat engines.

A number of studies have been conducted investigating the application of TEGs to heat recovery from automotive engines. As early as 1992 research at *Hi-Z technologies* investigated the design and production of a 1 kW thermoelectric generator for use in diesel truck engines (4). The purpose of the TEG was to recover waste heat from the truck exhaust gases providing electrical power to the vehicle and replacing the engine driven alternator. This would reduce the engine horse power leading to reduced fuel consumption and emissions. Due to the usage pattern of automobiles the TEG is subject to cyclic thermal loads, it is therefore difficult to predict the performance of TEG's in this application, they are also subject to mechanical degradation. The characterisation of the performance of TEGs in automotive applications was the subject of a different study by Tatarinov and Wallig (5) who had noted the difficulties presented by cyclic, inhomogeneous thermal and mechanical loading.

Another area that has seen lot of interest in the application of TEGs is in biomass fuelled cook stoves, most often for use in rural areas or in the developing world where access to grid electricity supply is limited or non-existent. Again at *Hi-Z technologies* research was conducted in 1996 by Killander and Bass (6) into a stove-top generator for use in rural northern Sweden. The generator gave the occupants of the home access to electric lighting and a few hours television in the evening where previously they had none. Further research into cook-stove generators in rural areas of Latin America found they were comparable in cost to photovoltaic solar arrays, simple to implement and provided a reliable, less intermittent source of power (7). Research conducted at Trinity College developed a cook-stove with an integrated TEG that provided an affordable light source and phone charger for use in rural Malawi. This provided off-grid power for communication and reduced the need to burn fossil fuels for a light source, in turn improving air quality and reducing risk of respiratory illness (8) (9).

*Figure 2: Completed Generator stove*

Clearly there is a wide range of areas in which TEGs can be utilised providing a number of benefits for people, the environment and industry depending on the application. As a result of this wide range of applications datasheets on TEGs are often insufficient as specified parameters do not match conditions in reality (10). For this reason it is desirable to characterise TEG performance over a wide range of parameters, in order to make reliable predictions about operation in the field.

## 1.3. Project structure

Following is a brief description of each chapter forming this project:

Chapter 1 is an introduction to the project. It analyses the current African situation and examines previous applications of TEGs for waste heat recover.

Chapter 2 describes the physical phenomena, related to thermoelectricity, that constitute the basis for understanding the contents of this project. The mechanical structure of a common commercial TEG device is also presented.

Chapter 3 presents the test rig developed in Trinity College to measure the electrical and thermal performance of TEG devices. The test rig allows the testing of a commercial thermoelectric module with control over temperature difference, mechanical and electrical load. Different test were carried out to study the energy balance across the TEG and the influence of the pressure. This chapter also compares the experimental results with theoretical models of its electrical characterization. Theoretical models will be used as a reliable tool to predict the performance and aid in the design of the thermoelectric prototype.

Chapter 4 presents the design, building, testing and evaluation of a thermoelectric device prototype that works as a collector and transformer of waste heat recovery into usable electricity.

Finally the general conclusion and suggestions of future work are discussed in Chapter 5.

# Chapter 2: Literature Review

## 2.1. The thermoelectric effect

Thermoelectricity is the direct conversion of temperature difference into electric potential or electric current into temperature difference. Thermoelectric effects encompass the Seebeck effect, the Peltier effect and the Thomson effect.

## 2.2. A brief history of thermoelectrics

### 2.2.1. The Seebeck Effect

The Seebeck Effect was first discovered in 1821 by Thomas Johann Seebeck. He connected two dissimilar metals B and C in a closed loop and held the junctions at different temperatures (Figure 3). He then placed a compass near the circuit and noticed that the needle of the compass deflected, demonstrating that a current was flowing.

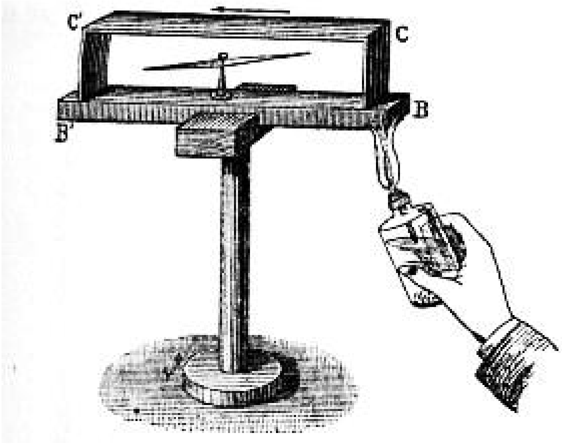

*Figure 3: Instrument used by Seebeck to observe the deflection of a compass needle (11)*

It was observed that the magnitude of the compass deflection was proportional to the temperature difference between the junctions (the larger the temperature difference, the greater the current generated).

The simple explanation behind this phenomenon is that electrons in the hot region are more energetic than those in the cold region. This creates a net diffusion of electrons from the hot end to the cold end which results in positive metal ions being left behind in the hot region and negative electrons accumulating in the cold region. This situation prevails until the negative charge in the cold end, repels further electrons migrating from the hot end. Consequently an electromotive force is generated, with the hot junction at higher potential

(12). It is important to note that this phenomenon only occurs when dissimilar metals are connected.

It was shown that the magnitude of the current flowing, depended on the actual resistance (and hence the specific dimensions) of the conductors concerned. Therefore it is preferable to consider an open circuit as shown in Figure 4, as the potential difference between the terminals depends on the temperature difference and not on the shape or dimensions of the conductors themselves (13).

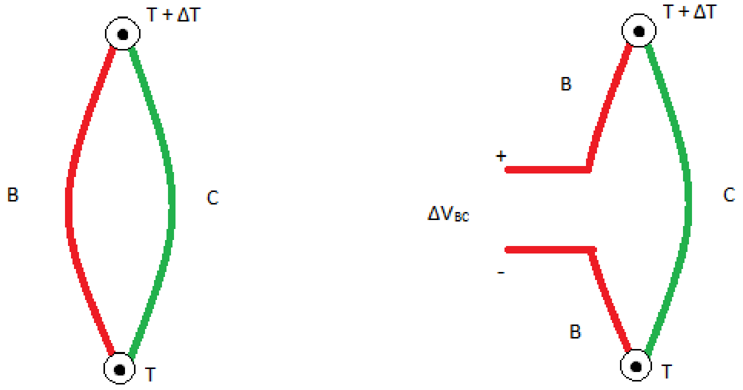

*Figure 4: The Seebeck Effect in a closed and open circuit respectively*

The relationship between the observed potential difference $\Delta V_{BC}$ and the temperature difference ΔT, is described in the equation below (13) :

$$\alpha_B - \alpha_C = \frac{dV_{BC}}{dT} \tag{1}$$

Where

- $\alpha_B$ is the Seebeck coefficient of conductor B $(V/K)$
- $\alpha_C$ is the Seebeck coefficient of conductor C $(V/K)$

Seebeck coefficients are dependent on the material, the molecular structure and on the absolute temperature of the material. They are non-linear as a function of temperature. However, if the Seebeck coefficient is relatively constant in the measured temperature range, the above formula can be approximated as:

$$\Delta V_{BC} = (\alpha_B - \alpha_C) \times \Delta T \tag{2}$$

In fact it is the relative or differential Seebeck Coefficient, that is of interest rather than the absolute Seebeck Coefficient of each material. The larger the differential Seebeck Coefficient, the greater the electromotive force generated.

$$\alpha_{BC} = \frac{\Delta \mathrm{V}_{BC}}{\Delta T} \tag{3}$$

### 2.2.2. The Peltier effect

The Peltier effect was discovered in 1834 by Jean-Charles Peltier. He noticed that when a current passed through two dissimilar metals in a closed loop, heat was evolved at one junction and absorbed at the other. The true nature of the Peltier effect was later explained by Lenz in 1838. It was demonstrated that the junction with the higher potential gave off heat to the environment and thus decreased in temperature. Likewise the junction with the lower potential absorbed heat and increased in temperature.

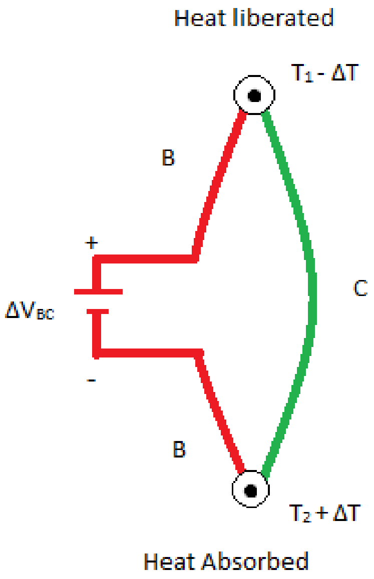

*Figure 5: The Peltier Effect*

The rate which is evolved or absorbed is proportional to the current flowing through the circuit.

$$\dot{Q}_{peltier} = \pi_{BC} \times I \tag{4}$$

Where

- $\dot{Q}_{peltier}$ is the rate which heat is absorbed or evolved $(J/s)$
- $\pi_{BC}$ is the relative Peltier coefficient of conductors B and C $(J/sA)$
- $I$ is the current $(A)$

The Peltier effect is caused by the change in entropy of the electrical charge carriers as they cross a junction (14). When electrons descend from the conduction band to the valence band, they dissipate energy in the form of heat. Likewise when electrons jump from the valence band to the conduction band, they need to absorb heat from their surroundings. The Peltier effect is reversible, unlike the Joule effect, and heat may be evolved or absorbed depending on the direction of the current and the temperature gradient.

### 2.2.3. The Thomson effect

William Thomson otherwise known as Lord Kelvin, discovered the third thermoelectric effect, which exists in a homogeneous conductor, known as the Thomson effect. Heat is absorbed or produced when current flows in a homogeneous material with a temperature gradient.

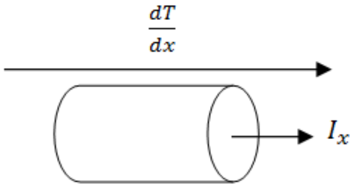

*Figure 6: A conductor with temperature gradient and electrical current*

If an electric current (of current density $J_x$) is passing through an individual conductor, and a temperature gradient $\frac{dT}{dx}$ is also present, then the net heat produced in the conductor per unit volume per second ($\dot{q}$) is given by (13):

$$\dot{q} = \frac{J_x^2}{\sigma} - \mu J_x \frac{dT}{dx} \tag{5}$$

The first term is the irreversible Joule heat. It is dependent on the electrical conductivity $\sigma$ and the square of the current density $J_x$. The second term is the thermoelectric heat. It is linearly dependent on the current density and the temperature gradient and can either absorb heat from the environment or dissipate heat. The coefficient $\mu$ is defined as the Thomson heat for the material and is temperature dependent.

Electric current flowing in the opposite direction to the temperature gradient will absorb energy. Conversely, electric current moving in the same direction as the gradient will dissipate energy (14).

If a single conductor without current flowing through it is heated at one point to a temperature $T_2$, a thermal gradient will exist on either side of the heated point. Two points $P_1$ and $P_2$ of equal temperature $T_1$ can be found as shown in Figure 7.

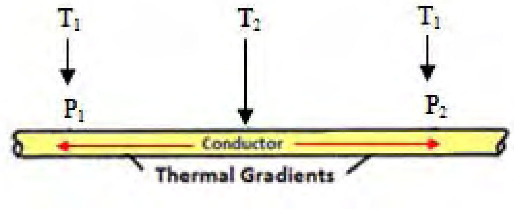

*Figure 7: Conductor temperature distribution when heated (15)*

If a circuit is constructed as shown in Figure 8, the temperature at $P_1$ and $P_2$ will change. This is due to the movement of the electrons with respect to the temperature gradient. Current moving against the thermal gradient will absorb energy and current travelling in the same direction as the gradient will dissipate energy. Heat will thus be absorbed at $P_1$, where the current direction is opposite to the heat flow, while heat will be liberated at $P_2$, where the current is in the same direction as the heat flow. The Thomson effects are equal and opposite and thus cancel each other. However when dissimilar metals are connected the Thomson effects are not equal and a flow of current results (15).

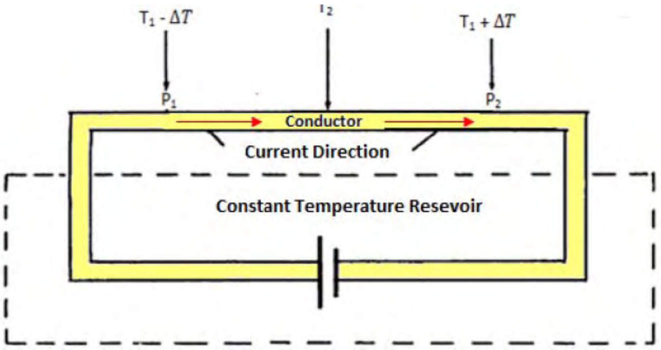

*Figure 8: The Thomson Effect (15)*

Equation 5 is the fundamental equation of thermoelectricity, however it is not entirely rigorous as it assumes that the irreversible Joule heat can be added to the reversible Thomson heat.

Thomson went on to derive the relationship between the Thomson heat (μ), the Seebeck coefficient (α), the Peltier heat (π) and the absolute temperature (T) of a conductor:

$$\mu = T \times \frac{d\alpha}{dT} \tag{6}$$

$$\pi_{BC} = \alpha_{BC} \times T \tag{7}$$

Integrating the Equation 6 gives:

$$\alpha(T) - \alpha(0) = \int_0^T \frac{\mu}{T} dT \tag{8}$$

It can be argued that when the absolute temperature is zero, $\alpha(0) = 0$

$$\alpha(T) = \int_0^T \frac{\mu}{T} dT \tag{9}$$

Therefore it is possible to determine the absolute Seebeck coefficient of a material based on the absolute temperature and the Thomson heat (13).

## 2.3. The thermoelectric power generation module

Thermoelectric modules (TEM) are solid state energy devices with no moving parts; they make use of the thermoelectric effect to convert energy. They can be used for cooling, heating, and energy generation:

- As a thermoelectric cooler (TEC), the TEM converts electricity into temperature difference. It has applications in thermal management and control of microelectronic devices.
- As a thermoelectric generator (TEG), the TEM converts heat directly into electricity. This project only focuses on thermoelectric generators which can be used to produce power in remote locations when temperature gradients are available.

The possibility of generating electricity from the thermoelectric effect wasn't realized until the end of the 19th century when Altenkirch demonstrated that ideal thermoelectric materials should possess large Seebeck coefficients ($\alpha$), high electrical conductivity ($\sigma$) to minimize Joule heating and low thermal conductivity ($\mathrm{k}$) to maintain the temperature difference between the junctions. These properties were embodied in the so-called figure-of-merit Z, where

$$Z = \frac{\alpha^2 \sigma}{k} \tag{10}$$

Since Z varies with temperature, the dimensionless figure of merit is defined as:

$$ZT = \frac{\alpha^2 \sigma T}{k} \tag{11}$$

In metals and metal alloys, the ratio of electrical conductivity to thermal conductivity is a constant (Wiedemann-Franz-Lorenz-Law). Therefore it is not possible to reduce the thermal conductivity without reducing the electrical conductivity. Consequently the metals best suited to thermoelectric applications are those with high Seebeck coefficients. However, most metals possess Seebeck coefficients of 10 $\mu V/K$or less, giving efficiencies of less than 1%.

In the late 1930's synthetic semiconductors were developed which possessed Seebeck coefficients in excess of 100 $\mu V/K$. Unfortunately in semiconductors, the ratio of electrical to thermal conductivity is less than in metals owing to their poor electrical conductivity. However it was found that the ratio could be increased by alloying the thermoelectric material with an isomorphous element or compound.

Heavily doped semiconductors are the best thermoelectric materials. The three leading materials are: Bismuth Telluride, Lead Telluride and Silicon Germanium.

In decreasing order of Figure-of-Merit (16):

1. Bismuth telluride and its alloys have the highest figure of merit ($3.4 \times 10^{-3}$ $K^{-1}$) but are limited to operating temperatures below 250°C.
2. Lead telluride and its alloys have a figure-of-merit in the region of $2 \times 10^{-3}$ $K^{-1}$ but can operate up to 500°C.
3. Silicon Germanium only has a figure-of-merit in the region of $0.8 \times 10^{-3}$ $K^{-1}$, however it can operate at temperatures up to 1000°C for long periods of time.

The most commonly used material in modern day thermoelectric modules is Bismuth Telluride.

Thermoelectric modules consist of an array of 2N pellets from dissimilar semiconductor material (p and n type) that make up N thermoelectric couples which are joined thermally in parallel and electrically in series, as shown in Figure 9 (17). They are sandwiched between two ceramic plates which are electrically insulating, but thermally conducting.

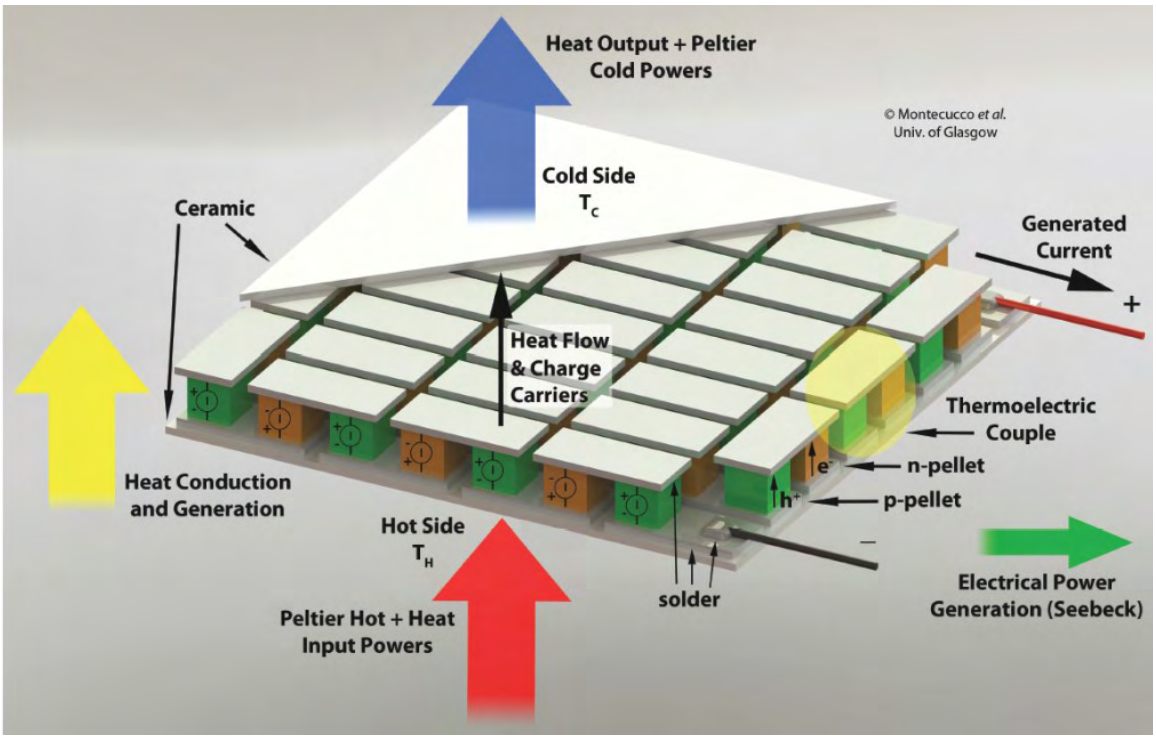

*Figure 9: Diagram of a modern day thermoelectric module* (18).

When heat is applied to one side of the p-n junction, this causes electrons in the n type material and holes in the p type material to gain kinetic energy and to be released into the conduction band (Figure 10). In the n type material, electrons flow from the hot side to the cold side. This causes a negative charge to build up at the cold end and a positive charge to build up at the hot end. In the p type material a positive charge builds up at the cold end and a corresponding negative charge at the hot end. If an external circuit is connected between the p and n junction, current will flow.

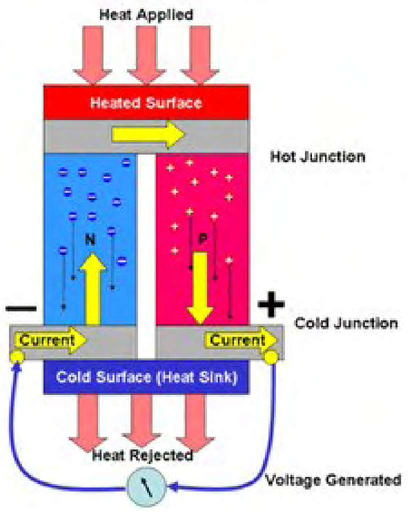

*Figure 10: The Seebeck Effect in a P-N junction (19)*

For a single thermocouple as picture in Figure 10, the electrical resistance R and thermal conductance K, for a thermocouple of length L and cross sectional area A, are given by:

$$R = \frac{2\rho L}{A} \tag{12}$$

$$K = \frac{2kA}{L} \tag{13}$$

Where

ρ: electrical resistivity equal to $\frac{1}{\sigma}$

k: overall conduction coefficient

# Chapter 3: Testing of thermoelectric generators

Often manufacturer's specifications for TEG performance are unavailable or inaccurate due to the wide range of application and load conditions in which they can be employed. Therefore, for precise the design of a thermoelectric device accurate data of the thermoelectric module is needed.

This section presents data and graphs describing the power produced at different temperature gradients, depending on the electrical load applied for a commercial thermoelectric generator (product code TG12-8 from *Marlow industries*). After gathering initial experimental data it is then possible to calculate mathematical models that allow the prediction of electrical values at each thermal operating point. The influence of mechanical pressure on TEG performance will be investigated too.

The whole project considers thermoelectric systems under steady-state operation and when in equilibrium.

## 3.1. Test rig design

An apparatus was designed in Trinity College in 2014 to allow accurate, reliable and repeatable testing of TEGs over a range of thermal, mechanical and electrical loads (8) .

This apparatus was used to characterize the performance of the TEG over a range of operating conditions. Figure 11 shows a schematic of the test rig.