TEG mounting

As explained in page 26, the TEG should be mounted using the compression method to maximize the heat transfer through the module. Therefore, the TEG is compressed between the hot plate and heat sink.

The compression was created with 4mm stainless steel screws on either side of the TEG. The screws were tightening carefully by applying torque in small increments with a torque screwdriver (torque pas screw of 1N.m), and alternating between screws to avoid damaging the ceramic plate of the thermoelectric module.

Special spring washers known as Belleville were ordered. The Belleville washers were introduced in the design to retain pressure on the stack when internal components expand and contract as a result of thermal expansion and contraction.

Insulation

Thermal insulation is required to reduce the carry-over from the hot side to the cold side outside the TEM thermal path. Base plate will get very hot and also the air above. To block it from heating up the heat sink by convection Superwool fibre paper was used. This material offers and excellent thermal insulation (thermal conductivity of 0.04 W/mK) in high temperatures (Maximum Operating Temperature of 1300°C). The same insulation material was placed below the hot plate (design in Appendix D) to avoid heat dissipation.

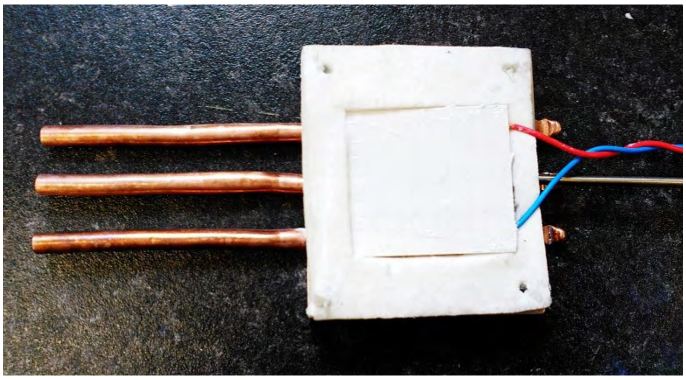


Figure 31: Insulation between hot base plate and heat sink

Furthermore, to block heat from transferring to the cold side through the fixating bolts insulated shoulder washers were used. The insulated shoulders were made of Nylon to handle high temperatures.

Instrumentation

To measure the temperature on both sides of the TEG, two thermocouples were placed on the hot plate and the heat sink as shown in **¡Error! No se encuentra el origen de la referencia.** so that the thermocouples could sit close to the TEG's side. Both temperatures are measured via a portable digital thermometer (HH506RA from *Omega*). Calibration of thermocouples is shown in Appendix B.

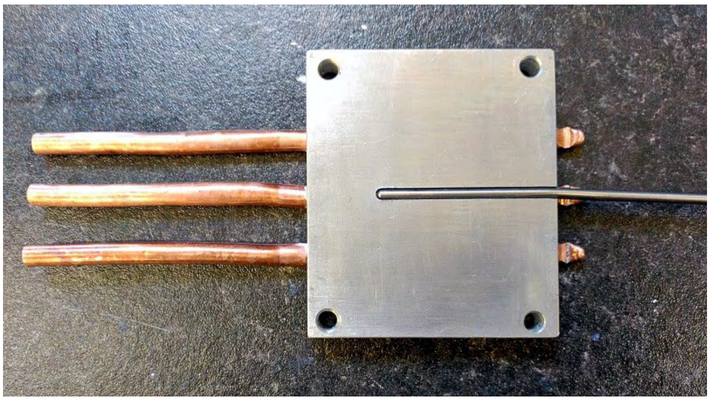
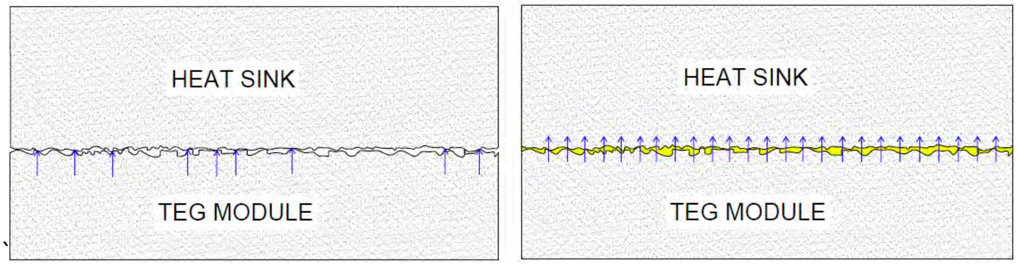


Figure 32: Thermocouple clamped on the hot plate to measure the TEG surface temperature

Heat transfer through all interfaces

Thermal adhesive was used to decrease thermal resistance in all interfaces of the device (TEG surfaces with heat sink and hot plate, heat pipes with hot plate and thermocouples with hot plate). The Figure 33 (a) shows that, under magnification, the surfaces consist of “hills” and “peaks”. When these two surfaces are brought into contact with one another, only the peaks make contact. The remaining “valleys” create voids through which heat energy can barely pass through, in effect creating an insulated area.



(a) (b)

Figure 33: (a) Contact without any thermal interface material (b) Contact using a thermal interface material

To improve heat transfer all the interfaces were throughly cleaned to minimise dust and contamination. Later, thermal interface material was used to fill the valleys and gaps. The material used has a much higher thermal conductivity than the air gaps it replaces. This essentiallly makes the entire interface tranfer heat instead of just where the peals were contacting.

Electronic circuit

The electronic circuit had already been designed and created in Trinity College. The main idea was to have a regulated output voltage to power the fan and other devices via an USB port. Since the TEG-module produce very low voltage (0-5V) a good voltage step-up and regulator was needed. The voltage step-up is a DC to DC converter circuit that increases the output voltage. Since it is a regulator, the output voltage will stay constant regardless of variations in the input voltage, load current, ambient or environmental conditions.

4.3. Testing

The experimental procedure was as follows:

- The infrared heating element was connected to a potentiometer (Carrol and Meynell CMV10E-1 variac). 500 W of power were delivered to the heat pipes in all the experiments.
- The input of the circuit was connected to the TEG. The output of the circuit was connected to a 5V fan.
- Hot and cold side temperatures of the TEG were directly read and manually entered in Excel.
- The TEG and fan current, voltage and power were measured and stored in the circuit card. All data was then exported and evaluated in Excel.

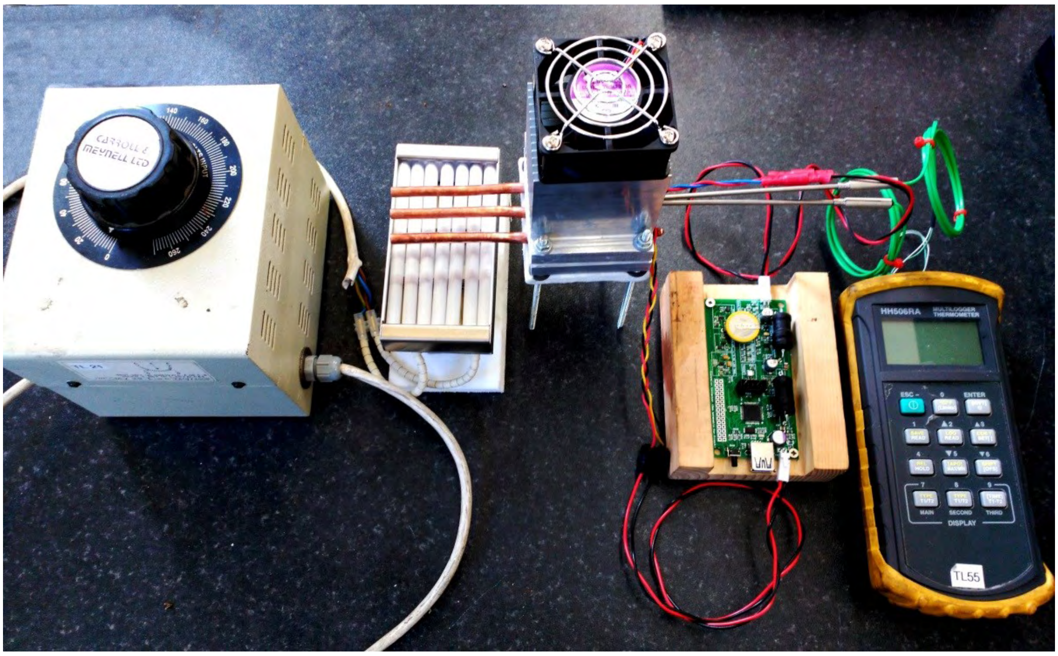


Figure 34: Overall instrumentation for the thermoelectric generator prototype

4.4. Evaluation

This section focuses on the determination of the maximum voltage and power generated by the system. The first part of this section analyses the open circuit operation. In this case the fan is powered by an external power supply and the open circuit voltage is measured. In the second part of this section, the fan is powered by the thermoelectric module and current, voltage and power are analysed.

4.4.1. Open circuit operation

In the first experiment the maximum open-circuit voltage generated by the TEG was only 0.47 V. In fact, the wavelength range of the infrared heating element is between 1.5 and 8 µm and the reflectivity of the copper heat pipe for this wavelength range is around 95% (28). That means that 95% of the incident radiant energy was reflected at the interface.

To improve the thermal transfer between the heat source and heat pipes an aluminium envelope was designed and built as shown in Figure 35. This design could more closely simulate the combustion stove scenario (Figure 2). The idea was to reflect the electro-magnetic radiation, trapping the air and thus increasing convective heat transfer. Aluminium was used because of its low emittance (emittance of 0.03) and high reflectance (reflectance of 0.97), which allows a good reflective insulation.

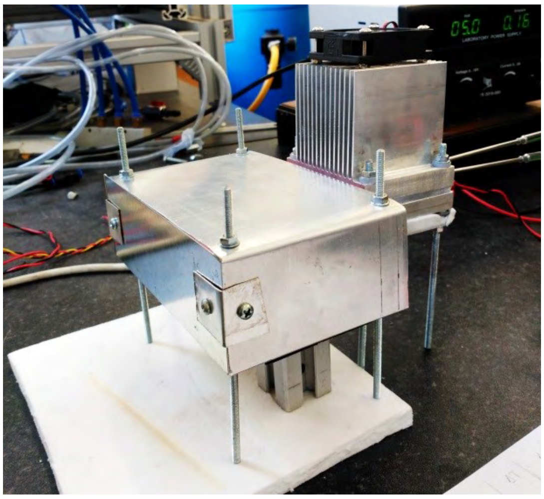


Figure 35: Aluminium envelope reflecting the electro-magnetic radiation

The second experiment using the reflecting envelope was conducted. As shown in Figure 37, the open circuit voltage increase significantly thanks to the reflection of the aluminium envelope. Nevertheless, the output voltage wasn't still enough to drive the fan.

Finally, to increase the thermal radiative transfer the heat pipes were sprayed with grade black paint (Black Matt Paint High Temperature from *Electrolube*) to absorb more heat radiation from the infrared heating element (Figure 36). In fact, black surfaces absorb all wavelengths of light and convert them into heat, so black heat pipes can get warm easily. As shown in Figure 37 , black heat pipes allow a significant improvement; a maximum voltage of 4.5 V was produce by the TEG.

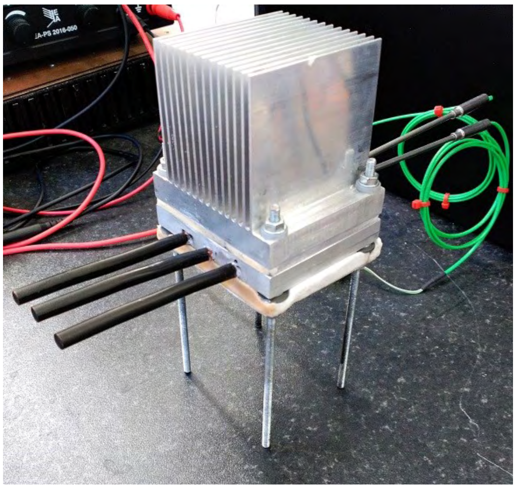


Figure 36: Heat pipes sprayed with grade black paint

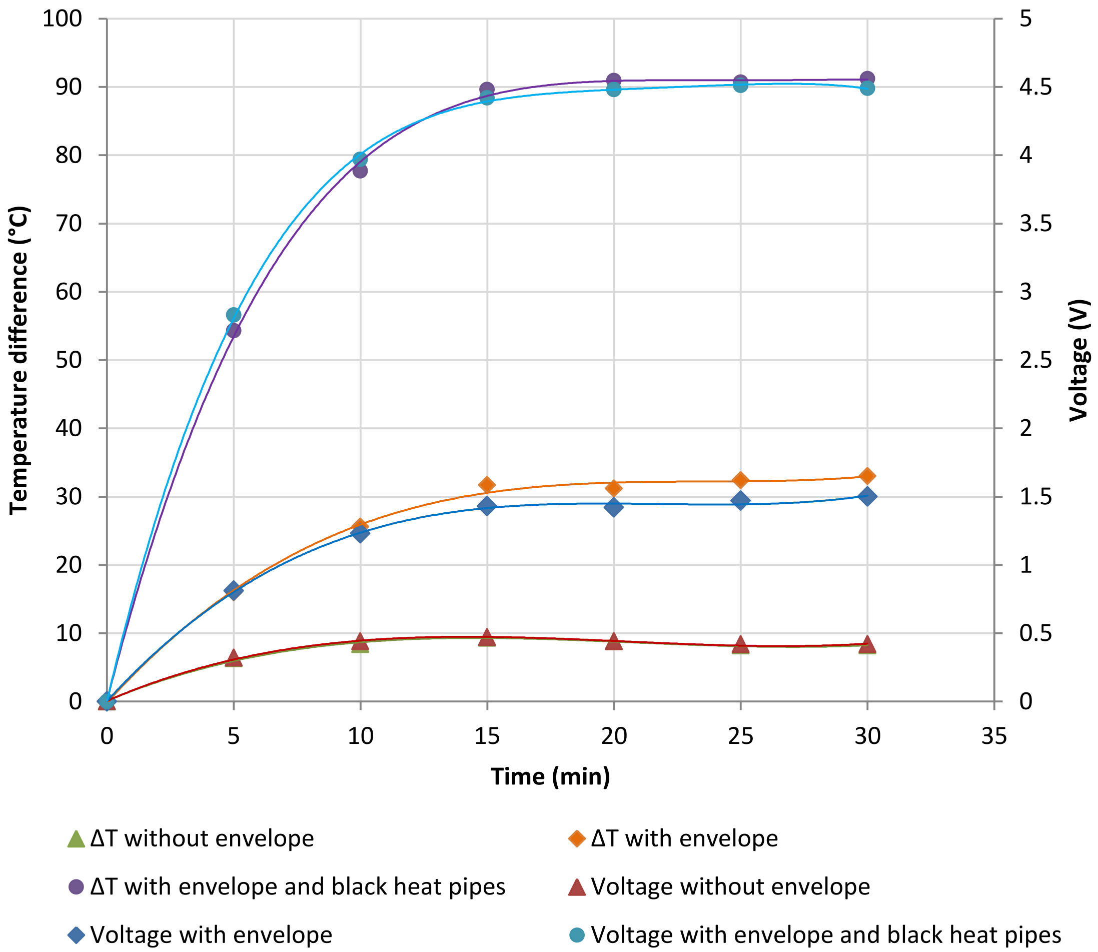


Figure 37: Temperature difference across the TEG (primary axis) and open circuit voltage generated by the TEG (secondary axis) in three different experiments.

4.4.2. Closed circuit operation

The maximum power transfer theorem demonstrated in Appendix A.2 states that in order to obtain maximum power from the thermoelectric module, the load resistance must be equal to the internal resistance of the TEG.

In this case the applied load is the fan, so the effective resistance of the fan must be equal to the internal resistance of the TEG. The effective resistance of the fan can be measured by dividing the voltage of the fan by the current going into it:

$$Effective\ Resistance\ of\ the\ fan = \frac{5\ V}{0.169\ A} = 29.58\ \Omega$$

The load resistance is much higher than the internal resistance (which is 2-3 Ω depending on the temperature difference across it). To maximize the power from the TEG the circuit was designed to change the effective load resistance and matched the internal resistance of the TEG. The load resistance was changed by varying the duty cycle which is defined as:

$$D = 1 - \frac{Vin}{Vout}$$

In the first experiment the fan was directly powered by the TEG. At the beginning the cold temperature remains the ambient temperature. But, with the heating process, the heat sink temperature rises too fast. In fact, natural air cooling method is not efficient enough to keep a low temperature on the cold side. From the Figure 38 it can be seen that the maximum temperature difference across the TEG was 50 °C. Therefore, the power delivered by the TEG was not enough to drive the fan.

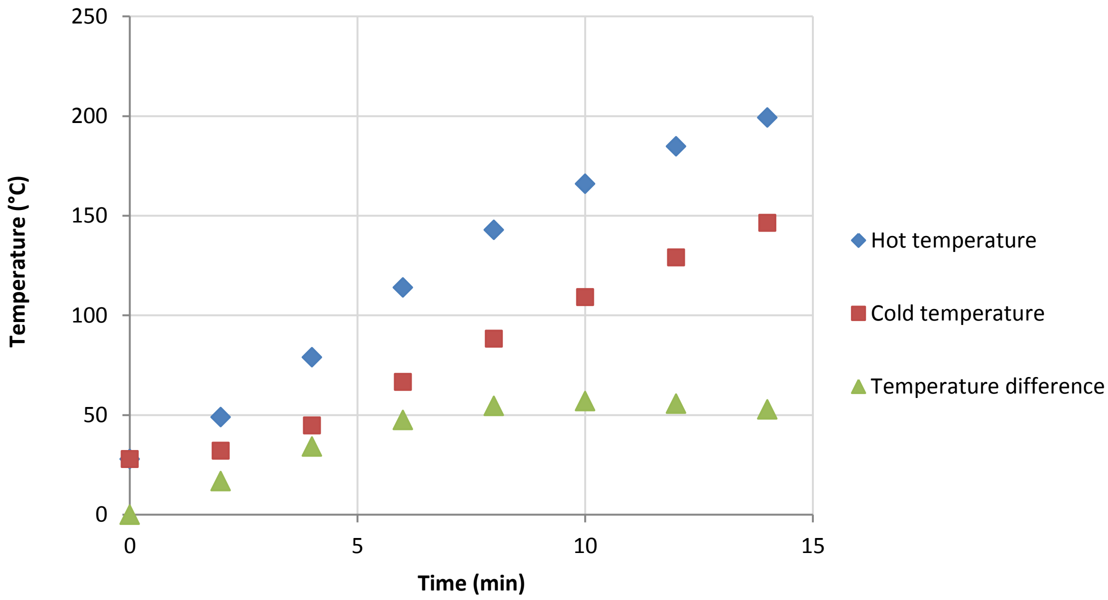


Figure 38: TEG temperatures when the fan is directly powered by the TEG

In the second experiment the TEG was connected to a 5V fan (load resistance). However, the heat sink was cooled via an external fan (same model as the load resistance) powered by a power supply. As shown in Figure 39 the cold temperature of the TEG rises slowly. Therefore temperature difference across the TEG can be kept about 85°C in steady state and the power generated by the TEG is high enough to drive the fan and another devices.

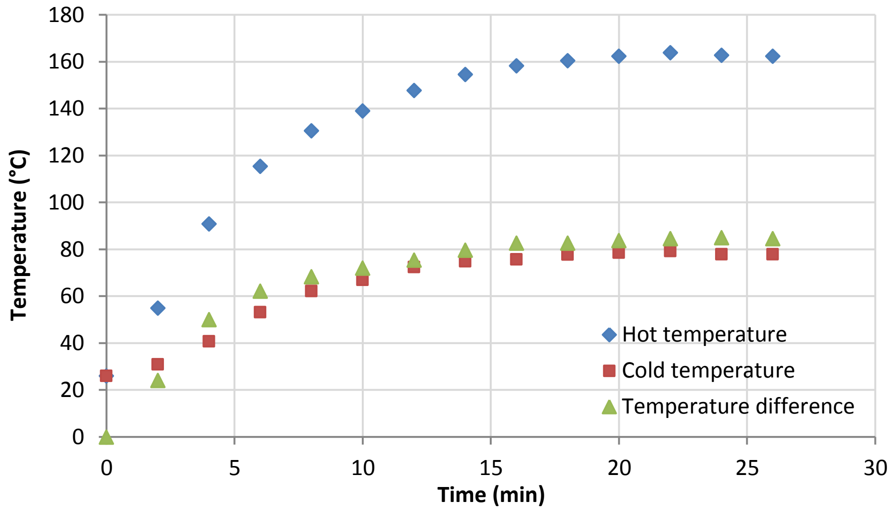


Figure 39: Temperature on both sides of the TEG when the fan was power by a power supply

Figure 40 displays the power produced by the TEG (P_in) and the power supplied to the fan (P_out) in W and Whrs. At ΔT~85°C and when steady state was reached, the power supplied to the fan was around 1W.

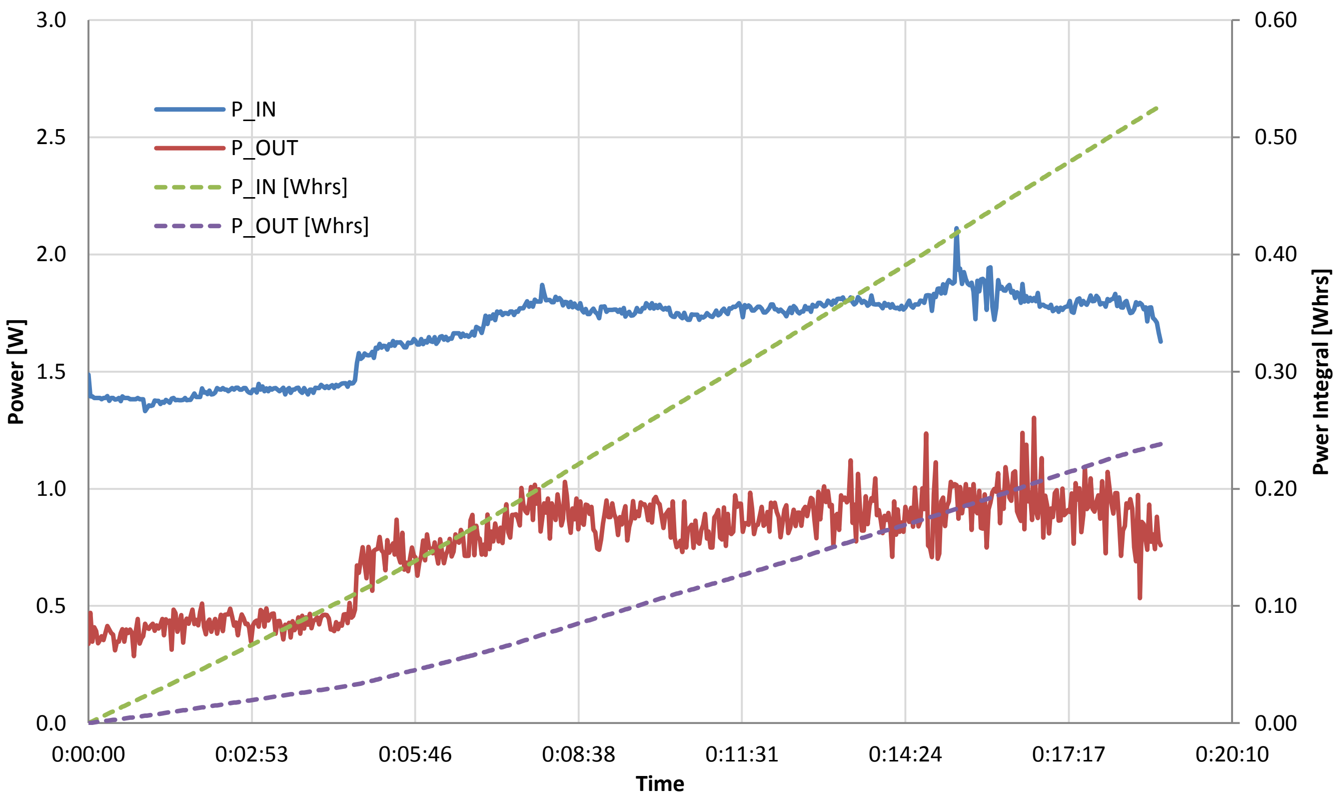


Figure 40: Power generated by the TEG and delivered to the fan as a function of time

Figure 41 illustrates voltage, current and duty cycle as a function of time. It can be seen that the fan starts rotating at 3.54 V and 0.095 A. When the steady state was reached the fan voltage remained at 4.5 V.

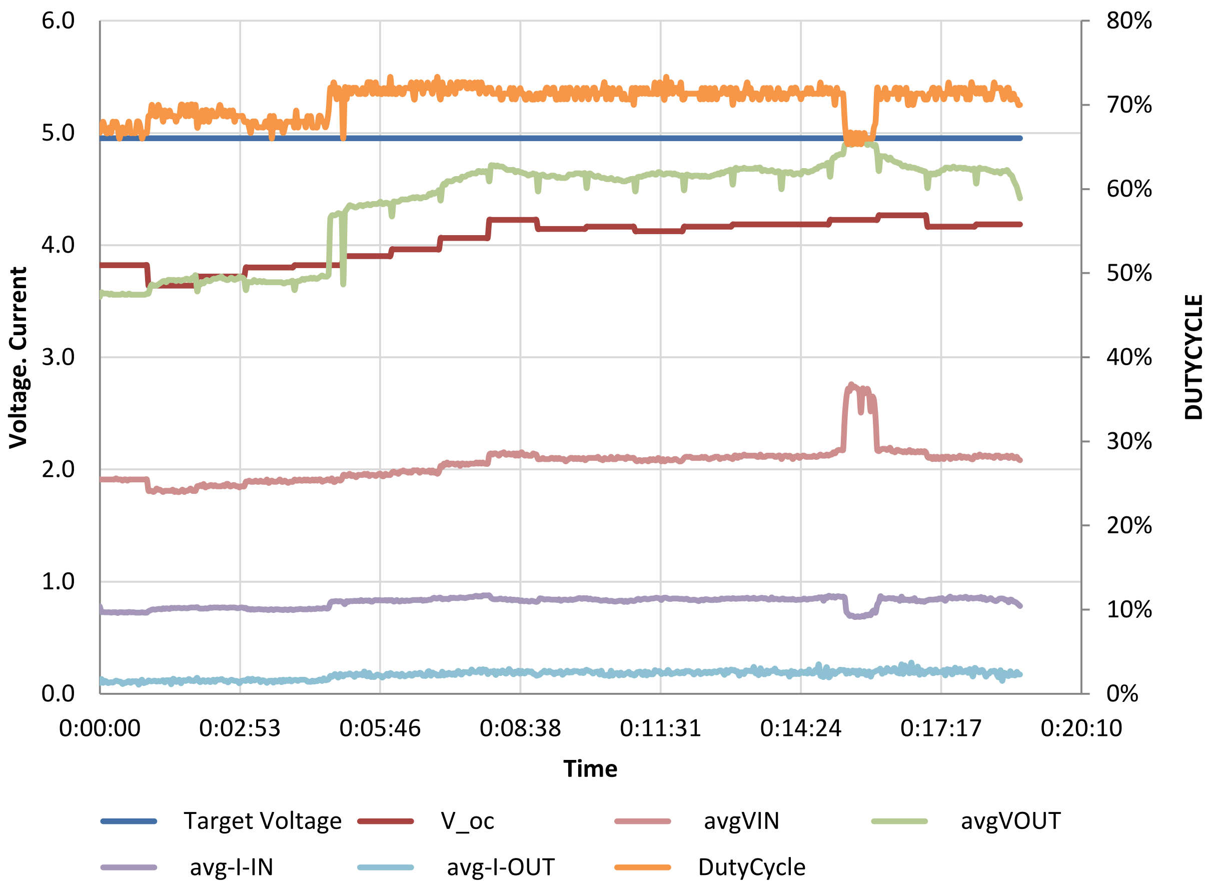


Figure 41: Voltage and current generated by the TEG and delivered to the fan as a function of time

The results in Figure 40 show that maximum power produced by the TEG is 2.15 W. Taking into account that heat source applies 500 W, the thermal efficiency of the device is very low. Therefore TE devices are acceptable for use in remote locations or in unusual situations. These include for power generation where conventional sources are unavailable or not replaceable. They constitute long-life power sources in which the heat from a cook stove can provide alternative energy. In addition of no moving parts, it does not affect the application, require replacement or maintenance.

In conclusion, the thermoelectric generator should be able to power the fan and more devices, as batteries and LEDs. Therefore the cold side temperature of the TEG has to be reduced. This means improving the heatsink or introducing an alternative cooling mechanism.

Chapter 5: Conclusion

Why use thermoelectric energy? The answer lies with renewable energy and today's need of energy sources in developing countries. Thermoelectric generators can provide energy in remote locations where waste heat is abundant and electricity is not. In developing countries around the world, access to electricity and even adequate lighting is a basic necessity unavailable. Thermoelectric generators could provide clean and safe energy, converting heat from cook stoves into energy for power LED lamps, charge batteries, mobiles phones and other devices.

In the first part, the project has presented an electrical characterisation of a commercial thermoelectric module. An in-depth analysis of the TEG performance is essential for the design of the thermoelectric prototype.

In the second part of this project, a thermoelectric generator prototype has been developed. After testing it, it was noted that the heat sink temperature increased very fast and as a result the power delivered by TEG was not enough to power the blower fan. Therefore improvements should be made to the thermoelectric design to increase the power produced and improve its operation. Future work is suggested to make the thermoelectric generator prototype a feasible system:

<u>Heat sink design improvement</u>

In order for the thermoelectric device to produce a high output voltage and current the optimisation of heat sink is required. The idea is to place the thermoelectric module under a water tank to increase heat transfer. The use of water guarantees that the cold heat sink temperature will always stay under 100°C.

Another alternative to improve performance is using a smaller heat sink surface (same size as TEG surface). This could avoid carry-over of heat flow from the heat to the cold sink.

<u>Experiments in real cooking stoves</u>

More experiments could carry out in order to incorporate the thermoelectric generator in a real cooking stove. Evaluation of stove design would be essential to maximize the temperature difference across the TEG. Furthermore, it would be interesting to study the possibility of charging LED lights, mobiles phones and radios from the thermoelectric generator.

<u>Study the thermal transients in thermoelectric system</u>

The overall project has considered thermoelectric systems under steady-state thermal operation, which is usually reached after several minutes. New articles (29) (30) consider the simulation of thermal transients found in practical thermoelectric systems, or effects due to the variation in the electrical system parameters. In fact, in most thermoelectric applications, such as the automotive field and stoves, the thermoelectric generators are subject to electro-thermal transients. Further study concerning thermal transients and dynamic characteristics of the thermoelectric device would be carried out.

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Appendix A: Calculations

A.1- Demonstration of the 1D conduction equation through the module

The rate of heat supply $\dot{Q}_H$ to the thermoelectric module can be estimated at the hot junctions as:

$$\dot{Q}_H = \frac{kA(\Delta T)}{L} + (\alpha_{p,n})T_H I - \frac{1}{2}R_{int}I^2$$

This equation is derived from the steady-state solution of the one-dimensional heat conduction equation for solids with internal energy generations in which is written as:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\dot{g}}{k} = 0$$

Where $\dot{g}$ is the rate of heat internally generated per unit volume (W/m^3), T is the temperature in Kelvin degrees function of the space x, and k is the thermal conductivity coefficient (W/mK).

Assuming constant temperatures at the hot and cold side as boundary conditions

$$T\,(0) = T_H$$

$$T(L) = T_C$$

Previous equation can be solved and the (parabolic) temperature distribution in the pellets is

$$T(x) = T_H - \frac{\dot{g}}{2k}x^2 + \frac{T_C - T_H + \frac{\dot{g}}{2k}L}{L}x$$

Combining this result to the equation of heat transfer $\dot{Q} = -kA \times \partial T/\partial x$ and considering that heat internally generated is caused by the Joule heating effect, the expression for heat flow through the hot side becomes

$$\dot{Q}_H = \frac{kA\Delta T}{L} - \frac{1}{2}R_{int}I^2$$

Taking into account the Peltier heating at the junctions this equation becomes

$$\dot{Q}_H = \frac{kA(\Delta T)}{L} + (\alpha_{p,n})T_H I - \frac{1}{2}R_{int}I^2$$

A.2- Demonstration of the maximum power transfer theorem

The maximum power transfer theorem states that in order to obtain maximum power from the thermoelectric module, the load resistance R_{load} , must be equal the internal resistance of the TEG, $_{Rint.}$ This section presents the proof of this theorem.

$$V_{OC} = IR_{int} + IR_{load}$$

Power to the load P_{elec}:

$$P_{elec} = I^2 R_{\ load} = \frac{V_{OC}^2}{(R_{load} + R_{int})^2} R_{load}$$

Let $R_{int} + R_{load} = x$

$$P_{elec} = \frac{V_{OC}^2}{x^2}(x - R_{int}) = \frac{V_{OC}^2}{x} - R_{int}\frac{V_{OC}^2}{x^2}$$

$$\frac{dP_{elec}}{dR_{load}} = \frac{dP_{elec}}{dx} \times \frac{dx}{dR_{load}}$$

$$\frac{dP_{elec}}{dx} = -\frac{V_{OC}^2}{x^2} + 2R_{int}\frac{V_{OC}^2}{x^3}$$

$$\frac{dx}{dR_{load}} = 1$$

$$\frac{dP_{elec}}{dR_{load}} = \left(-\frac{V_{OC}^2}{(R_{load} + R_{int})^2} + 2R_{int}\frac{V_{OC}^2}{(R_{load} + R_{int})^3}\right) \times 1$$

For maximum power:

$$\frac{dP_{elec}}{dR_{load}} = 0$$

Therefore:

$$\frac{2R_{int}}{(R_{load} + R_{int})} = 1$$

This means:

$$R_{int} = R_{load}$$

A.3- Additional data concerning electrical characterisation for constant temperature difference across the TEG

Figure 42 shows the power generated in response to the load resistance for a range of temperature differences. The experimental data is compared with the theoretical predictions provided by the effective model. These curves allow highlighting the importance of the load matching to perform TEG operation. As can be seen in the figure, the power significantly decreased the further the load resistance deviated from the internal resistance of the TEG.

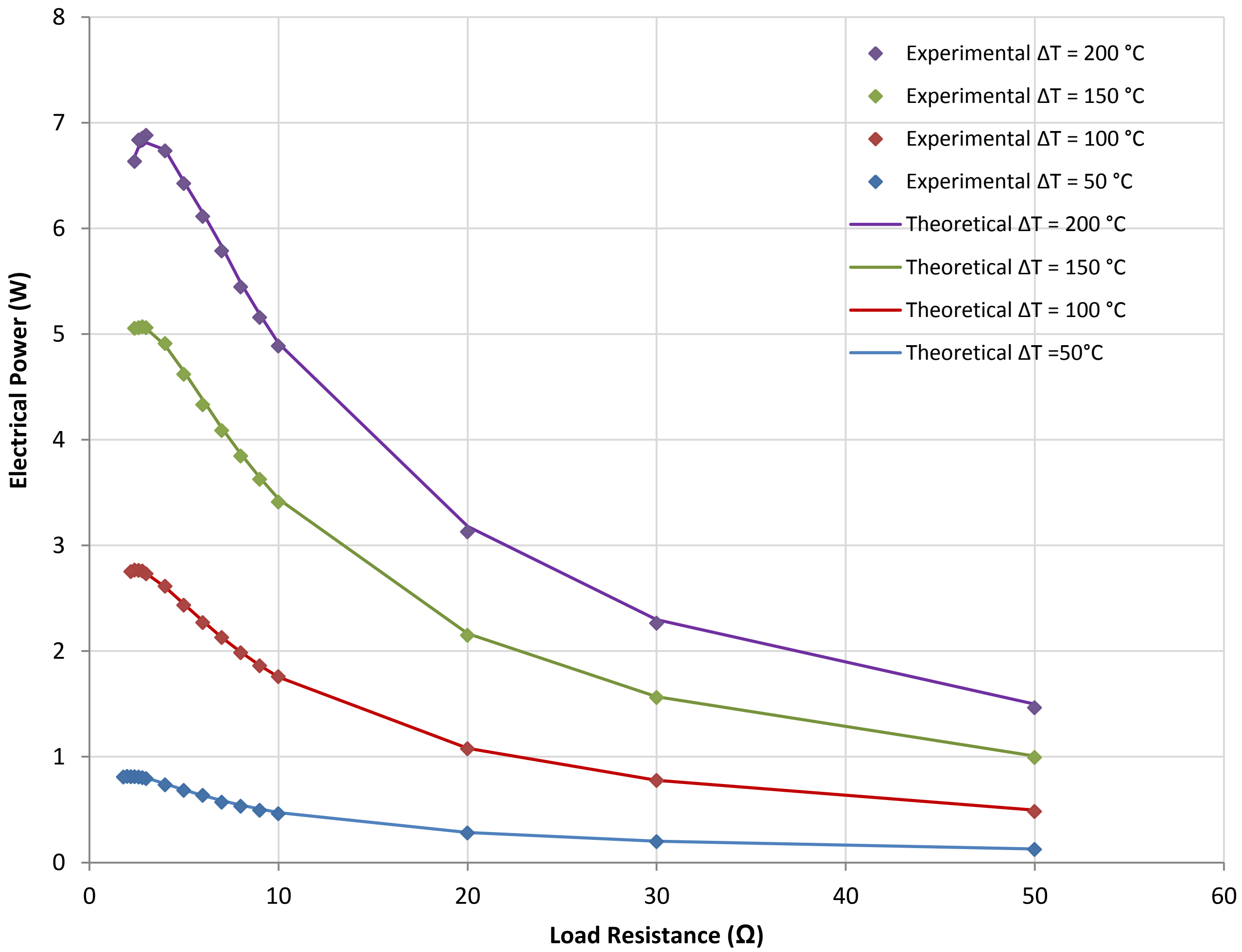


Figure 42: Measured and predicted TEG performance using the standard model and the effective Seebeck coefficient model for different temperatures across the TEG

The equation of experimental power as a function of load resistance can be accurately estimated using a sixth degree polynomial regression line from experimental data. The matched resistance, which corresponds to the resistance leading to the maximum power point, is obtained setting the derivative of the regression line equal to zero and computing iterative calculations by Excel. Finally, the maximum electrical power can be obtained. Final results are shown in Table 4.

ΔT (°C)	Maximum Power (W)	Matched Load Resistance (Ω)	α effective (V/K)	Rint (Ω)	Open circuit Voltage V_{OC} (V)	Voltage to match load V_{opt} (V)	Ratio V_{opt}/V_{OC}
50	0.810	2.086	0.0526	2.095	2.6331	1.3370	0.5078
100	2.764	2.478	0.0522	2.471	5.2039	2.6751	0.5141
150	5.071	2.751	0.0522	2.772	7.4530	3.8045	0.5105
200	6.892	3.060	0.0459	3.054	9.1291	4.6355	0.50778

Table 5: Relevant data concerning the electrical characterisation of the TEG.

Appendix B: Calibration of Thermocouples

The temperature was measured using K-type thermocouples which were read direcly in a portable digital thermometer. The thermocouples were calibrated using an RTD temperature probe.

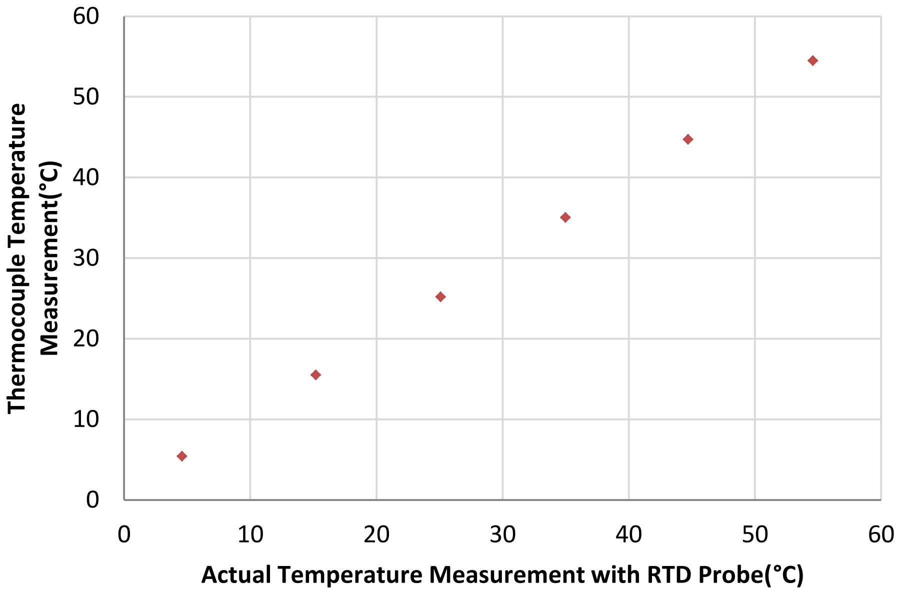


Figure 43: Calibration of Hot Side Thermocouples

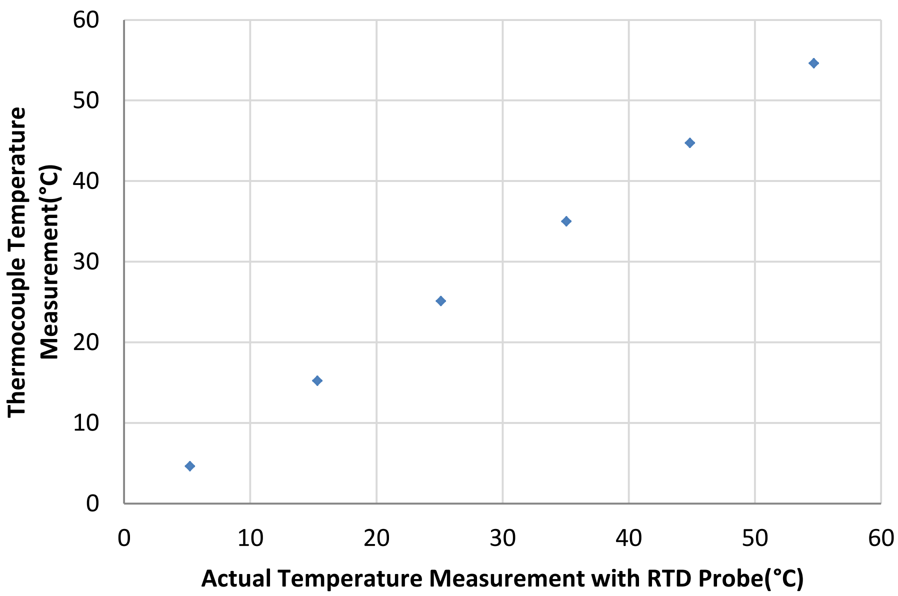


Figure 44: Calibration of Cold Side Thermocouples

Appendix C: Project Budgeting

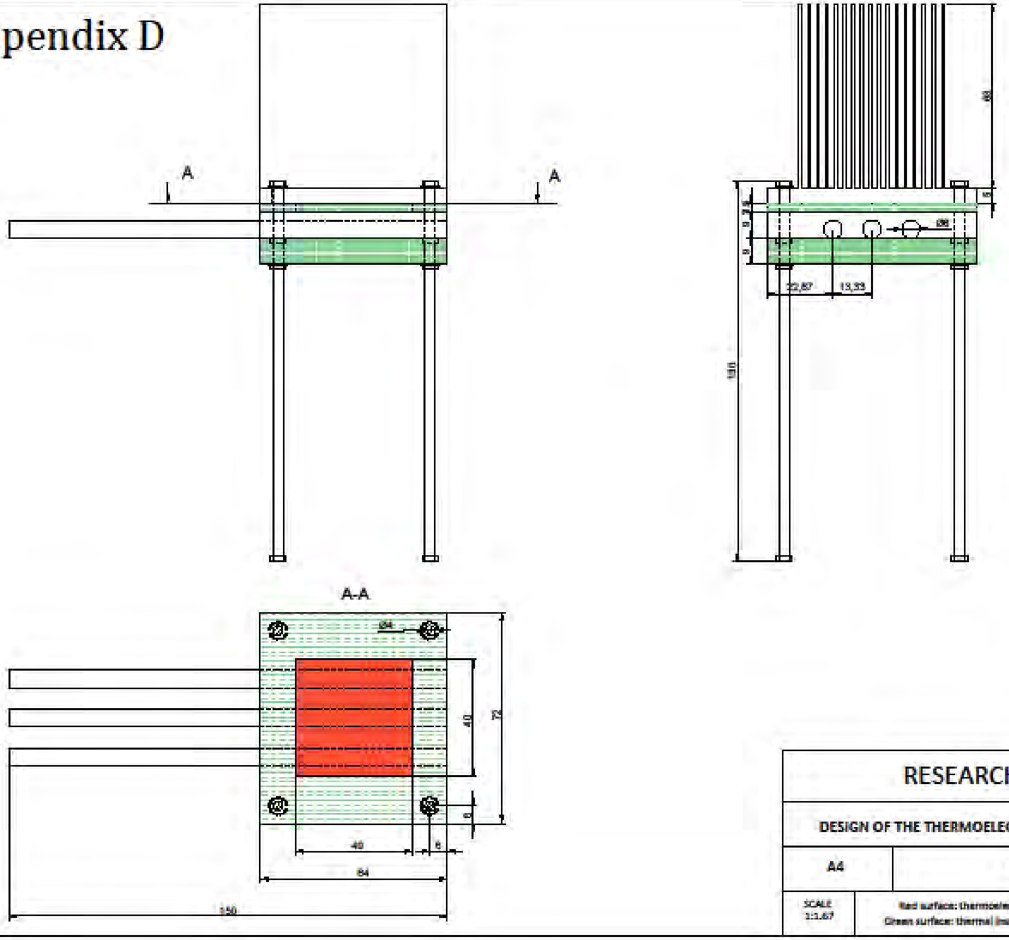
The following table includes the following expenses categories:

1- Research equipment: these include purchases needed to carry on the research and construction of the thermoelectric device.
2- Labour costs: these include the salary cost for doctors, supervisors and any academic support I have recruited to assist in the project.

EXPENSES				
Research Equipment				
Product	**Units**	**Cost per unit in €**	**Total cost in €**	
TEG Module	2	63	126.00	
Infrared Heating element	1	18.75	18.75	
Thermal Paste	1	15.96	15.96	
Heat pipe	3	14.45	43.35	
Superwool fibre paper	1	31.52	31.52	
Insulated shoulder washers	4	0.52	2.08	
Thermocouples	2	23.76	47.52	
Black Paint	1	16.5	16.50	
Photocopies	200	0.05	10.00	
Labour Costs				
Labour	**Name**	**Euros/hour**	**Total hours**	**Total cost in €**
Supervisor	Tony Robinson	36	5	180
Doctor	Maurice Seady	30	2	60
Doctor	Séamus O'Shaughnessy	30	3	90
Workshop staff	Mick Reilly	25	2	50
Total Expenses in €				
Research Equipment	311.68			
Labour Cost	380.00			
Total	691.68			

Table 6: Project Budgeting

Appendix D



RESEARCH PROJECT		
DESIGN OF THE THERMOELECTRIC GENERATOR PROTOTYPE		
A4	CELIA LOPEZ GASCON	
SCALE 1:1.67	Red surface: thermoelectric module Green surface: thermal insulating material	Page 58 of 60