Test Bench for Measuring the Electrical Properties of Commercial Thermoelectric Modules

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Abstract

One of the most promising applications of thermoelectricity is the recovery of waste heat for the production of electrical energy. Nowadays, several thermoelectric companies manufacture commercial thermoelectric modules (TEMs) based on Bi_2Te_3 compounds specially designed to perform as Seebeck modules.

This paper describes a test bench (geometry, materials, measuring equipment) to analyse the behaviour of this type of modules working under several temperature differences (ΔTs). This allows to estimate the potential electric power generated in an application where the optimum ΔT cannot be achieved because the amount of heat supplied by the heat source is too small, or there is a limitation in the heat dissipation capacity at the cold side. The paper also shows the results obtained using two commercial modules tested under different working conditions. Plots of voltage, electrical power generated, and efficiency versus electric current generated are also included.

Introduction

The use of thermoelectric generators (TEGs) for recuperating residual heat recovery at low temperatures (100-300ºC) is achieving great interest [1]. Its simple design combined with an easy control and its low maintenance implies a reduction in total costs. Furthermore, no fuel system is required to supply the heat, and even the low energy conversion factor of TEGs is not a great disadvantage taking into account that this type of heat cannot be used to generate electricity using conventional techniques [2]. Thermoelectric generators can be used to produce electricity from many waste heat sources, for instance the exhaust gases of the automobiles can be used [3], [4], [5]; equipments can be also installed to take advantage of the waste heat contained in oil and natural gas well-head equipment such as pilot flames, reboiler glycol loops, and exhaust, [6]. The company Evaporative_Sytems sells commercial TEGs for those applications. The use of the heat from garbage incineration and plants for combustible solid waste can be also profitable [7], [8].

Nowadays, there are several companies in the world manufacturing TEMs based of $BiTe_2$ alloys specially designed for generation applications (Hi-Z, Eureca Ltd, Altec, Thermonamic…).

Our research group is interested in this type of heat recovery and has developed some works in this area [9], [10], and [11]. A collaboration with the Spanish Government was signed two years ago in order to analyse the potential of heat residual recuperation in the industrial and domestic sector. One part of this project consisted of developing a test bench which allows to estimate the behaviour of TEMs as generators. The test bench was designed to reproduce normal working conditions in commercial applications. The main idea was to obtain values of the total energy conversion of the system, always considering those results obtained represent minimum values when the system is designed specifically, that is, the thermal bypass is minimised or special materials are used. Furthermore the test bench was designed to be simple and was built using commercial products in order to minimise its cost. In the following sections the test bench is described, giving also considerations for cases where accuracy need to be improved. Finally the results obtained in the analysis of a commercial module are presented, just in order to show that the system is able to reproduce the normal behaviour of this type of module. Similar characterization are shown in [12], [13], and [14]. In this articles the heat transmission from the heat source is also analysed.

Description of the test bench

The test bench was designed to analyse the behaviour of two modules simultaneously. As shown in Fig.1, it has 5 main components described in next paragraphs.

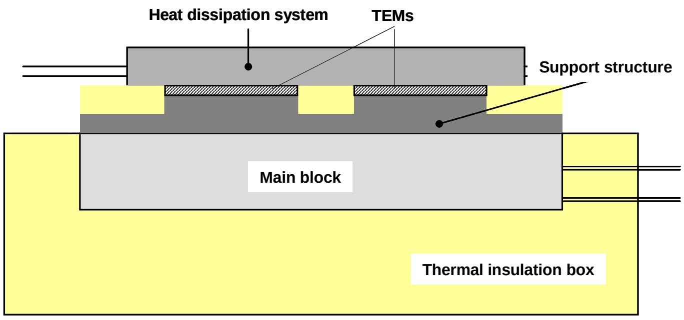


Figure 1. Scheme of the test bench

<u>The thermoelectric modules</u>

In the design of a test bench, some characteristics of the TEMs to be analysed sets dimensions and materials to be used. Initially this test bench was developed to study the performance of 62 x 62 mm square modules (standard dimension for all companies). HZ14 module was taken as reference because is one of the commercial module used commonly in Seebeck applications. As shown in Hi-Z web page, this module is optimised to work with ΔTs around 200ºC and with a maximum temperature at the hot side of 250ºC. The manufacturer indicates that the thermal flux required to generate 13 W is 9,54 W/cm^2 approximately, and considering the dimensions of the module (39.31 cm^2 cross section), a heat power of 375 W per module is required. Mounting aspects of the modules are explained in [15].

The main block

It is the part of the test bench where the heating power is generated. The main block comprises two plates: the upper block, where the electrical resistors are fixed (see Fig. 2), and a thin plate joined to the first one by 16 stainless screws.

With respect to the material used in its construction, a good thermal conductor is required in order to transfer the heat from the electrical resistors and to achieve a good temperature uniformity at the free surface of the main block where the support structure will be positioned. Two possible materials were duralumin and copper, (see their thermal properties in table 1).

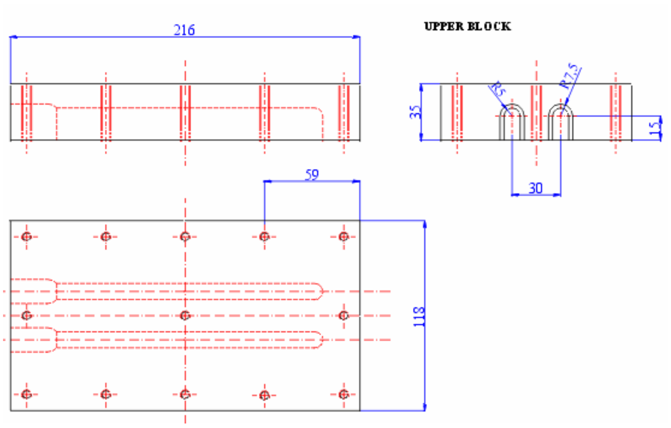


Figure 2. Scheme of the upper block

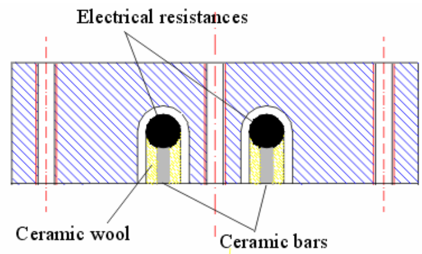


Figure 3. Scheme of the electrical resisors location

Although the thermal behaviour of copper is better than duralumin, the later was chosen because of its better properties to be mechanised. Furthermore, the dimensions of the block (216 x 118 x 35 mm) would increase significantly the cost of the prototype if copper is used.

	Duralumin	**Pure copper**
	4.4 Cu, 1.0 Mg, 0.75 Mn, 0.4 Si	
ρ [kg/m^3]	2770	8933
λ [W/mK]	174	401
c_p [J/kgK]	875	385
Melting point (ºC)	503	1085

Table 1. Thermal properties of duralumin and copper

Considering the optimum working conditions of HZ14 modules. The heat source must be able to supply more than 800W, taking into account the thermal losses around the test bench. The heat generation capacity is supplied by two cylindrical resistors (10 mm diameter) with a length of 160mm and a nominal value of 1 Ω, able to stand working temperatures up to 400ºC. They were positioned in two grooves made in the main block, (see Fig. 2). Another option was to mechanise two cylindrical holes in the main block with a geometric tolerance, but making so long cylindrical holes with high accuracy is quite complex, being equally effective the use of grooves. The distance between the upper part of the electrical resistance and the free surface is 1 cm, enough distance to achieve a good temperature uniformity on this surface.

In order to assure a good thermal contact between the electrical resistance and the main block, two thin bars of ceramic material pressed the resistances against the upper part of the main block, (see Fig. 3). A fibre-glass panel was inserted between the upper block and the lower aluminium plate, see (Fig. 4). This panel reduces the heat transmission from the electrical resistances to the lower part of the test bench and avoids the possible movement of the electrical resistances. The free space between the resistances and the grooves was filled with a ceramic wool (λ=0.5 W/mK) able to stand temperatures up to 1000ºC.

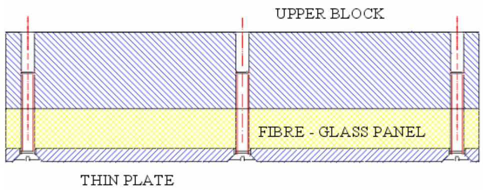


Figure 4. Different components of the main block

One advantage of this construction is that if the temperature of the thin plate is stabilised at the temperature of the upper block, all the thermal power supplied by the electrical resistors can be considered as the heat transmitted to the support structure, except for the small thermal losses at the sides.

The thermal insulation box

A thermal insulation box surrounds the main block. The purpose of this box was to reduce the thermal losses of the heat source and as a first approximation be able to considered that the electrical power consumed by the resistors was the heat power which crosses the TEMs.

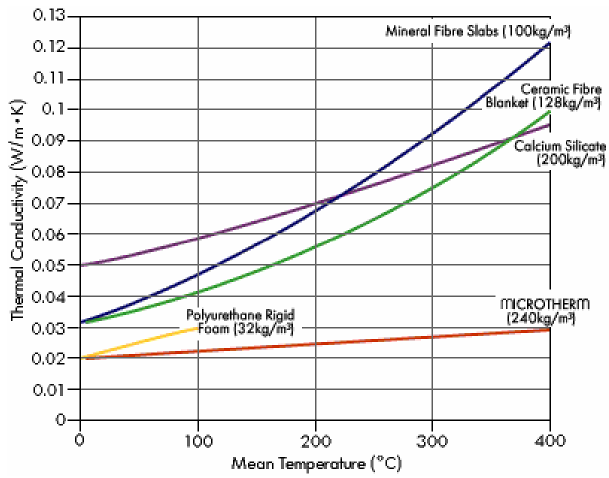


Figure 5. Thermal conductivity of different insulation materials (Microtherm graph)

In applications performing at room temperatures, the best cost-effective materials are polyurethane and polystyrene foams, whose thermal conductivities are around 0.03 W/mK. However both materials increase their thermal conductivity with temperature and their maximum working temperature is around 90ºC.

As shown in Fig. 5, materials based in silica powder (as Microtherm insulants) vary slightly their thermal conductivity in all the working range temperature of this test bench but its price is quite high when small quantities are required.

Therefore, fibre-glass panels have been used. This material has a thermal conductivity between 0.032 and 0.045 W/mK at room temperature, stands steady temperatures around 250ºC (500ºC when it is glued) and maintains a good behaviour with temperature (0.08 W/mK at 300ºC). Nevertheless, in order to avoid a direct contact between the insulation material and the main block, its laterals have been covered with ceramic plates (0.5 W/mK), with a thickness of 6 mm which support working temperatures over 1400ºC, (see Fig. 6).

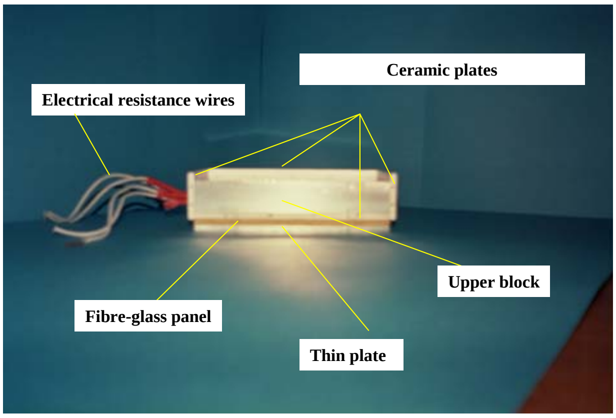


Figure 6. Photo of the main block mounted

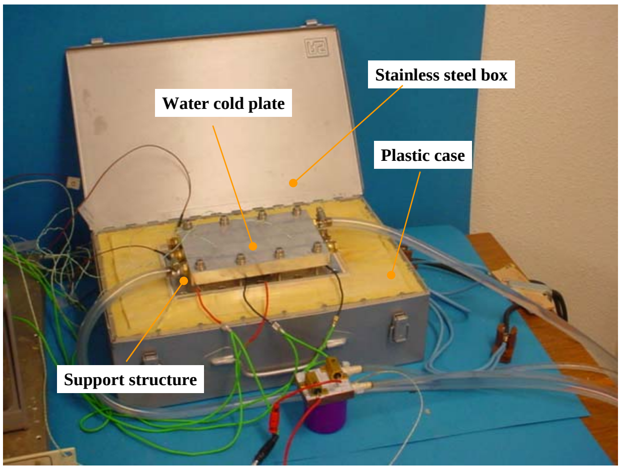


Figure 7. Test bench

In order to assure a good contact between the panels and the main block, a casing made of polycarbonate was fixed between the stainless steel box and the outer fibre-glass panels. This casing is a critical component because its maximum working temperature is 90ºC. However, just only the area close to the edges of the main block attain high temperatures. Other possible solutions are metacrylate (limit temperature 120ºC) or PTFE (250ºC), with a thermal conductivity of just only 0.1 W/mK.

Support structure

The support structure, (see Fig. 8), is the flat aluminium plate where the TEMs are positioned. On the base of this plate, two heat spreader were mechanised with a 65 x 65 mm square cross section and a height of 12 mm. The heat spreaders were positioned symmetrically occupying 33% of the support structure.

The main function of this support structure is to re-conduct most part of the thermal flux supplied by the heat source through the modules. The free surface of the heat spreaders were lapped in order to reduce the thermal contact resistance with the modules.

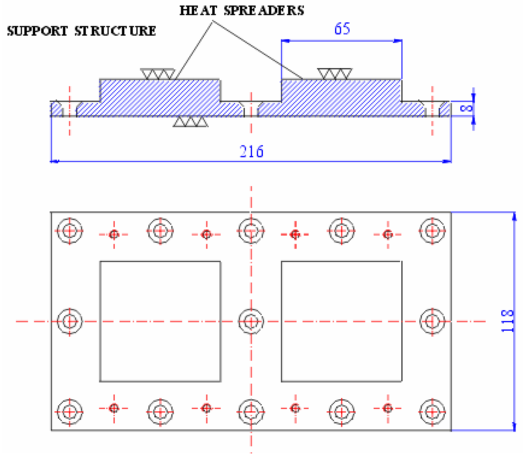


Figure 8. Support structure

The difference between the area occupied by the modules and the dimensions of the support structure is justified depending on the type of heat source used. For low temperature, or low heat power, which are the characteristics of the mayority of the heat sources, it is very convenient to collect heat from a surface larger than the TEMs. This support structure can admit several modifications depending on the number of modules tested. The support structure can also be analysed trying to optimise different aspects such as the height of the heat spreaders; the shape of the joints between the spreaders and the base of the support structure (in our case in right-angle); the thickness of the plate or even the material. The height of these spreaders must be a compromise between the reduction of the thermal bypass losses and the cost and weight of the structure, taking into account the gain in weight which in some applications can be a critical variable (for example in TEGs for vehicles).

Using 16 stainless steel screws, the support structure is joined to the main block that simulates the waste heat source, applying a thermal grease between both surfaces to diminish the contact thermal resistance.

The sides of the heat spreaders and the base of the support structure were also covered with ceramic plates to avoid the direct contact between them and the insulation material.

Heat dissipation system

Any heat exchanger can be mounted at the cold side of the thermoelectric modules.The result shown in this article were obtained using an aluminium water cold plate. The heat dissipation capacity was high enough to study the performance of TEMs at its optimum working point. Furthermore it allows for controlling the temperature at the cold side with high accuracy.

A photograph of the test bench is shown in Fig. 7

Limitations of the test bench

The DC Source used to feed the electrical resistors can be regulated in voltage (0-20 V) and current (0-50 A). Although the nominal value of the electrical resistances is 1 Ω, this value increases with temperature, so the maximum electrical power supplied was 756 W.

With respect to the steady maximum temperatures at the test bench, apart from the temperature limit of the TEMs, and although the melting point of duralumin is 502ºC, it was not advisable to work with temperatures higher than 300ºC (in order to avoid possible softening in the joints).

Taking into account the free surface of the main block (216 x 118 mm), different configurations can be tested using the same water cooling plate depending on the size of the TEMs, for instance: 3 HZ14, 2 HZ20 or 10 Peltier modules (40 mm square section).

Measurement equipment

The water flow was measured with a KEY INSTRUMENTS rotameter (Model FR-4500) with an accuracy of ± 3% full scale. Taking into account that this type of flow meter is not very accurate, the calculation of the heat power dissipated using the water flow measured must be considered with caution.

The voltage of the TEMs was measured with a multimeter FLUKE 179 in 600 mV and 6 V scale (±0.09% of reading + 2 counts accuracy in both cases). This multimeter measured the voltage drop, including the internal resistance of the amperimeter and the electrical load. The electric current generated by the modules was measured with a multimeter Silver UT-55 using two scales 200 mA (±0.09% of reading + 1 count) and 20 A (±2% of reading + 5 counts)

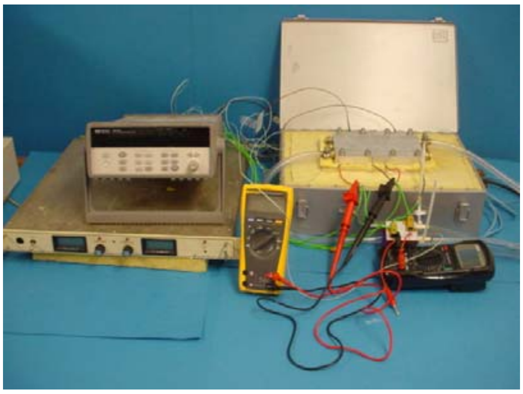


Figure 9. Test bench with the measurement equipment

Temperature readings were done using thermocouples (type K). This sensor consist of a 1 m length of thermocouple wire (0.2 mm ϕ) terminated in a moulded on miniauture thermocouple plug; its working range is from –50ºC to 450ºC. The thermocouples were connected to a Data-Logger HP34970. This system allows for representing the thermal transients until achieve the steady conditions. The same type of thermocouples are used to measure the water temperatures. A photograph of the test bench with all the measurement equipment is shown in Fig. 9

Type of experiments

Two type of test were performed:

- Type A. The temperature at both sides of the module were controlled. The temperature at the cold side was maintained at 30ºC as the temperature at the hot side was varied in a range between 50ºC and 230ºC using increments of 20ºC.
- Type B. Only the temperature at the cold side was controlled and maintained at 30ºC. The electric power supplied to the electrical resistors was increased from 50W to 700 W in increments of 50 W. That is, the temperature at the hot side of the module was a degree of freedom.

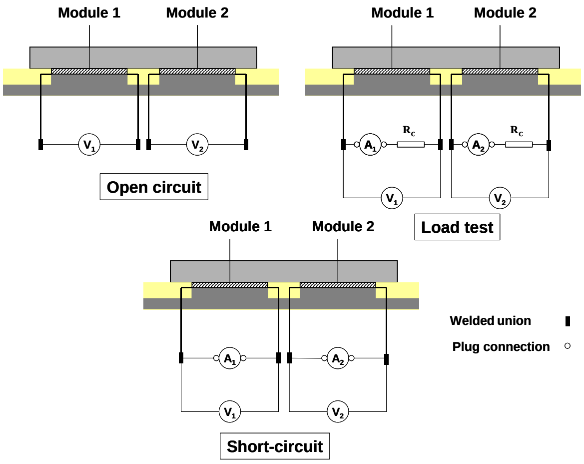


Figure 10. Schemes of different measurement connections

In both cases the TEMs were analysed working in open circuit, with nominal electric loads of 15 Ω, 1Ω, 0.5 Ω, 0.15 Ω, 0.01 Ω and 0.05 Ω, and in short circuit (see Fig. 10). The electrical loads were also cooled in order to keep a constant value since an increment of temperature can vary the value of the electrical load been difficult to analyse the behaviour of the TEMs for low electrical load. The electric resistors where soldered to the wires of the TEMs, however the real electric loads (Rc_r) calculated after the measurements of voltimeter and amperimeter was higher than the theoretical value (Rc_t). This is important when low values of resistances are analysed. It is not easy to test the TEMs working with electrical loads under 0.05 Ω. In order to obtain results at this points the last test was done connecting just the amperimeter.

Results

Previously to comment the results obtained, variables shown in graphs or tables are briefly explained.

Variables of the heat exchanger

W_e: Electric power consumed by the electrical resistors.

$\dot{Q}_{H_2O}$:Heating power dissipated at the cold side. It is calculated using equation:

$$\dot{Q}_{H_2O} = \dot{m}_{H_2O} \cdot \bar{\rho}\big|_{H_2O} \cdot \bar{c}_p\big|_{H_2O} \cdot \left(T_{H_2O}\big|_{out} - T_{H_2O}\big|_{in} \right) \quad \{1\}$$

where:

$\dot{m}_{H_2O}$: volumetric water flow, [l/min]

$\bar{\rho}\big|_{H_2O}$: water density

$\bar{c}_p\big|_{H_2O}$: water specific heat

$T_{H_2O}\big|_{outlet}$:water temperature at the inlet of the cold plate

$T_{H_2O}\big|_{inlet}$: water temperature at the outlet of the cold plate

All the water properties were evaluated at the mean temperature between the inlet and the outlet

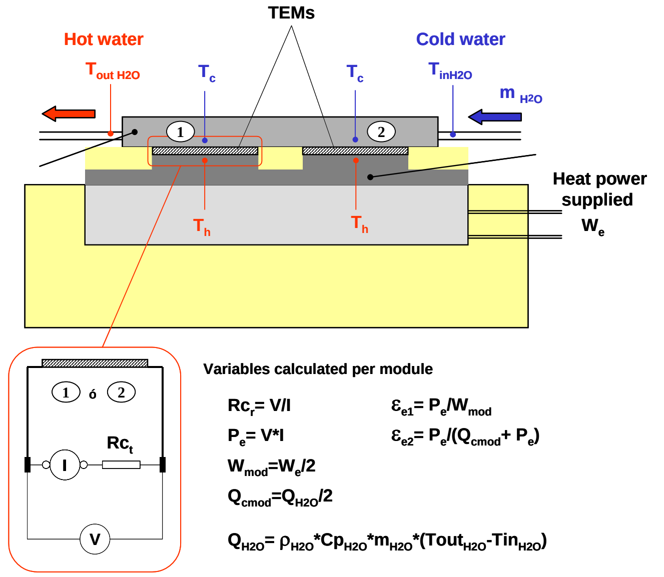


Figure 11. Scheme with the variables included in graphs and tables

Variables of the thermoelectric modules:

V_i: voltage generated by module i

I_i: electrical current generated by module i

P_{ei}: electric power generated by module i.

T_{h_i}, T_{c_i}: Temperatures at the hot and cold side of the module. T_h and T_c were not measured in direct contact with the faces of the module. The thermocouples were positioned inside the support structure and the cold plate approximately 1 mm from the real faces of the TEM. Being both components made of aluminium, the temperature difference between the faces of the TEM and the temperature of aluminium are not significant. This option was chosen in order to avoid the use of grooves in the surfaces in contact with the modules.

Just in order to calculate the energy conversion efficiency some assumptions were done. The electric power consumed by the test bench was equally spread between the two TEMs due to the symmetrical configuration. A little temperature difference exists at the cold side between the modules, however this difference is negligible. In this way and defining the heating power per module (W_{mod}) as half of W_e, a value for the electric efficiency of the TEMs is obtained using the following equation:

$$\varepsilon_{e1}\big|_i = \frac{V_i \cdot I_i}{W_{mod}} \qquad \{2\}$$

Notice that the real efficiency of the module will be higher, because the net heat power which crosses the module is lower since W_{mod} includes three types of thermal losses:

- Thermal losses through the thermal insulation surrounding the test bench
- Thermal bypass through the screws which join the cold plate to the support structure
- Thermal bypass through the insulation material at the support structure

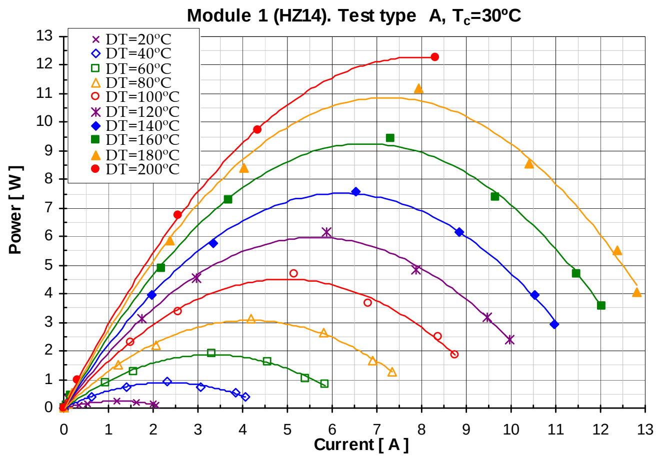
A second way of calculating the electric efficiency is using the value of the power dissipated at the cold side.

$$\varepsilon_{e2}\big|_i = \frac{P_{e_i}}{\frac{\dot{Q}_{H_2O}}{2} + P_{e_i}} \qquad \{3\}$$

If water flow and temperatures are measured with high accuracy, equation (3) gives a more exact value of the electric efficiency of TEM, but also the value obtained will be lower than the real one of the module. Notice that the heat power dissipated by the cold plate includes the thermal bypass losses in the support structure (screws and insulation). Due to the value of the specific heat of water, small variations in the measurement of the water flow causes errors non-negligible in $\dot{Q}_{H_2O}$; specially in those cases where the power consumed by the test bench is small.

Results type A: tests for different ΔT

The electric power curves of Graph 1 show a maximum for every value of ΔT equal to the internal resistance of the module, this value increased with the temperature difference, and was used to create graphs 3 and 4 (maximum electric power generated)

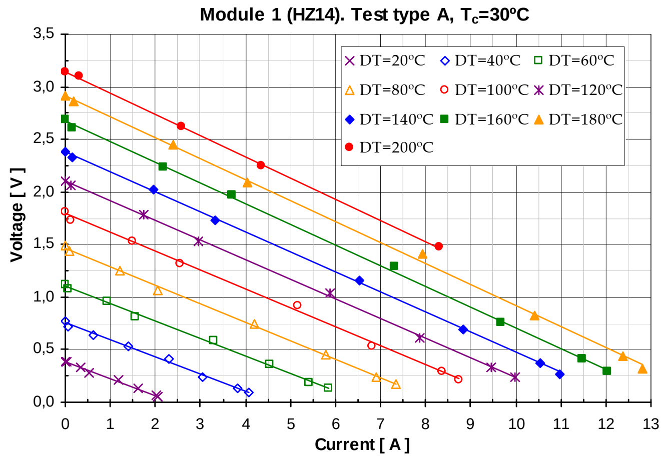


Graph 1. Curves power - current for different ΔT, test type A

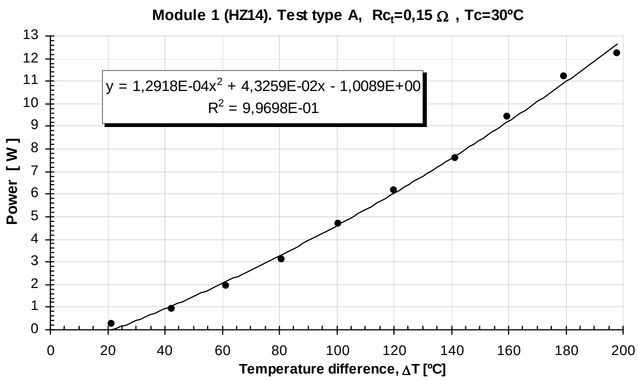
The results obtained in both modules were very similar, so just only graphs and tables for one of them are shown in the article. The maximum electric power generated with module 1 for a ΔT of 200ºC was 12,26 W, and 12.06 W for module 2 with electric efficiencies of 3.42 % and 3.36 % using the first method in its calculation.

These results are consistent with the values given by the manufacturer: HZ14 module is able to produce at least 13 W with a ΔT of 200ºC and an efficiency of 4.5%. The discrepancy in the efficiency could be accounted for by the fact of including the thermal losses in the amount of heat which crosses the module. Furthermore, the heating power per module 358.79 W is similar to the one indicated by Hi-Z (9.54 W/cm^2) which multiplied by its cross section (6.2 cm x 6.2

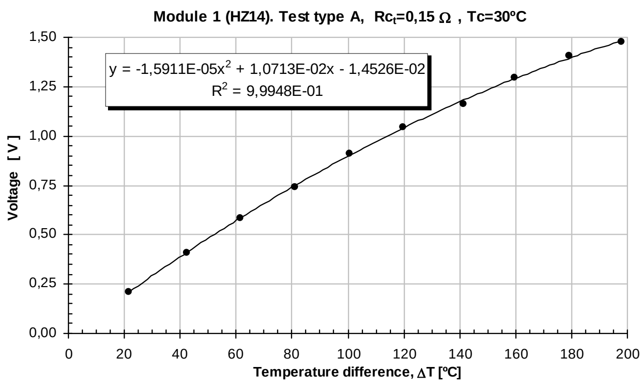
cm) gives a thermal power 366.7 W, dividing the minimum power (13W) by this quantity the efficiency would be 3.54 %. The discrepancy in the power generated can be attributed to an excess of thermal grease in the interface between the modules and the support structure, or at the water cold plate. Notice also that the real electrical load connected 0.178 was a little higher than the theoretical internal resistance of the module (0.15 Ω ± 0.05 Ω) and the ΔT measured includes the contact thermal resistance being the temperature difference at the module lower.



Graph 2. Curves voltage - current for different ΔT, test type A



Graph 3. Power generated for different ΔT, Rc_t=0.15 Ω



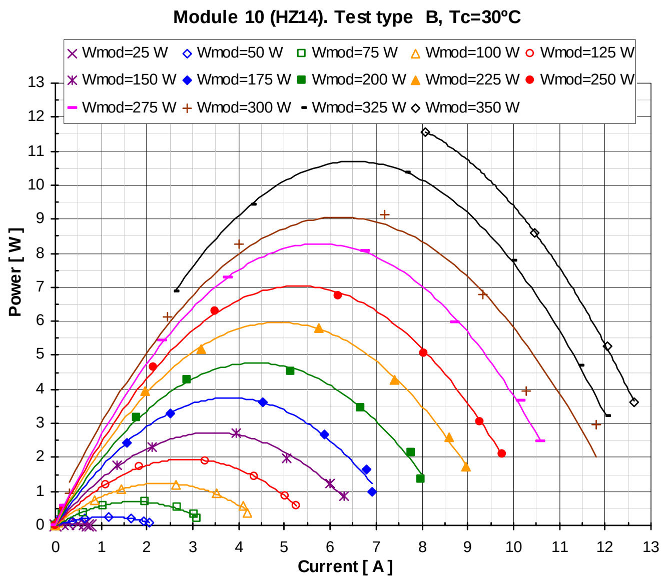
Graph 4. Voltage for different ΔT, Rc_t=0.15 Ω

As shown in graphs 1 and 2, for a ΔT of 200ºC there are not measurements for electric loads lower than 0.1 Ω. The limit of the DC employed in the tests did not allow to obtain results working with electric loads equal or lower to that value, more heating power was required in this case to achieve the ΔT of 200ºC because of the Peltier effect.

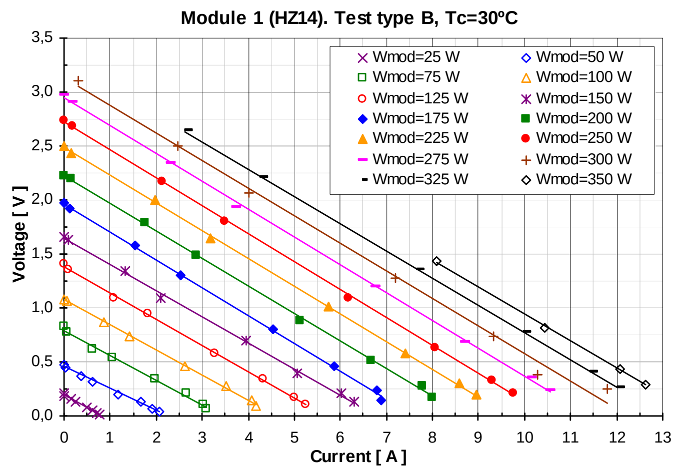
Module 1 (HZ14)		**Type A**						
Tc≈30ºC R_{ct}≈0.15 Ω								
W_{mod}	**T_h**	**T_c**	**ΔT**	**V**	**I**	**Rc_r**	**P_e**	**ε_{e1}**
W	**ºC**	**ºC**	**ºC**	**V**	**A**	**W**	**W**	**%**
37,38	50,67	29,06	21,61	0,211	1,19	0,177	0,25	0,67
79,05	71,36	29,05	42,31	0,407	2,30	0,177	0,94	1,18
119,03	90,68	29,32	61,35	0,585	3,30	0,177	1,93	1,62
133,10	110,20	29,32	80,87	0,742	4,19	0,177	3,11	2,34
192,72	130,00	29,42	100,59	0,912	5,15	0,177	4,70	2,44
224,36	150,45	30,54	119,91	1,044	5,89	0,177	6,15	2,74
261,63	171,94	30,66	141,28	1,162	6,54	0,178	7,60	2,90
293,93	190,14	30,64	159,50	1,294	7,30	0,177	9,45	3,21
317,06	209,46	30,22	179,24	1,410	7,94	0,178	11,19	3,53
358,79	228,19	30,09	198,11	1,475	8,31	0,178	12,26	3,42

Table 2. Performance of module 1, different ΔT, Rc_t=0.15 Ω

Results type B: tests for different heating powers

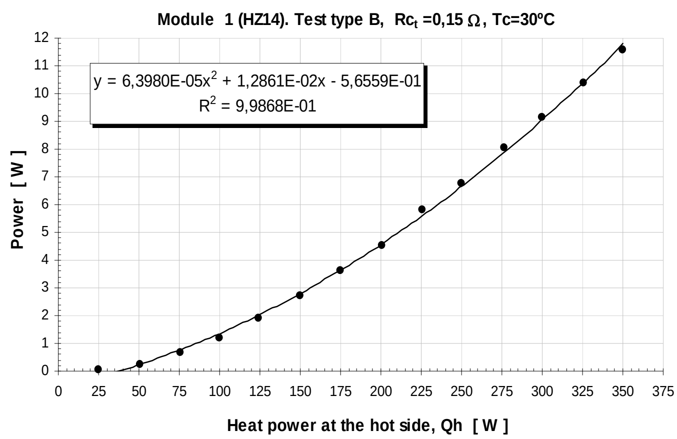


Graph 5. Curves power - current for different ΔT, test type B

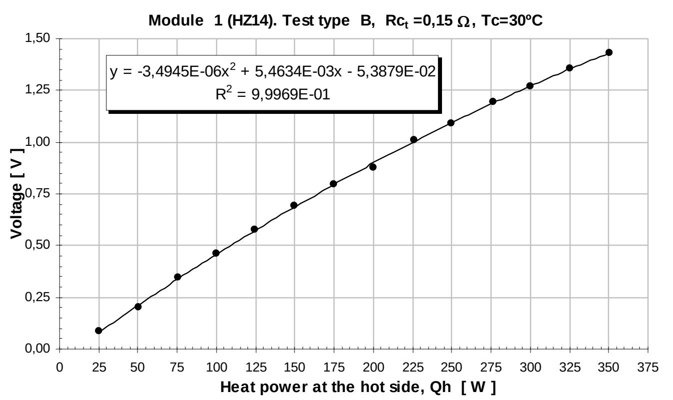


Graph 6. Curves voltage - current for different ΔT, test type B

Similar graphs have been generated for several values of W_{mod} instead of several values of ΔT. Graphs 5 to 8 are equivalent to graphs 1 to 4 but using waste heat power as the reference.



Graph 7. Power generated for different heat power at the hot side, Rc_t=0.15 Ω



Graph 8. Voltage generated for different heat power at the hot side, Rc_t=0.15 Ω

Module 1 (HZ14)		Type B						
Tc≈30ºC R_{ct}≈0.15 Ω								
W_{mod}	T_h	T_c	ΔT	V	I	Rc_r	P_e	ε_{e1}
W	ºC	ºC	ºC	V	A	W	W	%
25,22	39,61	30,46	9,15	0,085	0,49	0,174	0,04	0,17
50,69	51,68	30,13	21,55	0,203	1,16	0,175	0,24	0,47
75,98	66,92	29,93	36,99	0,345	1,97	0,175	0,68	0,90
99,84	80,81	30,79	50,02	0,459	2,62	0,175	1,20	1,20
124,61	93,70	30,18	63,53	0,574	3,28	0,175	1,88	1,51
149,76	108,46	30,45	78,01	0,692	3,94	0,176	2,73	1,82
175,14	122,52	30,51	92,01	0,798	4,54	0,176	3,62	2,07
200,41	136,54	30,23	106,32	0,879	5,13	0,171	4,51	2,25
225,78	152,79	30,34	122,45	1,011	5,74	0,176	5,80	2,57
249,67	165,50	30,22	135,28	1,092	6,18	0,177	6,75	2,70
276,32	182,43	30,15	152,28	1,192	6,75	0,177	8,05	2,91
299,92	197,49	30,55	166,93	1,270	7,19	0,177	9,13	3,05
325,44	213,85	30,54	183,30	1,353	7,66	0,177	10,37	3,19
350,24	229,87	30,22	199,66	1,431	8,09	0,177	11,57	3,30

Table 3. Performance of module 1, different heating powers, Rc_t=0.15 Ω

In this type of test, there are no results for electric loads higher than 0.15 Ω. for high heat powers. The temperature at the hot side of the module surpassed the steady limit temperature indicated by the manufacturer (250ºC). The maximum temperature at the hot side allowed during the test was 230ºC.

The results obtained in both type of test allow to estimate the potential electric power generated in an application where the optimum ΔT cannot be achieved because the amount of heat supplied by the heat source is too small, or there is a limitation in the heat dissipation capacity at the cold side. Normally manufacturers just only includes data for the matched load and the optimum temperature difference.

Test connecting the modules in electrical series

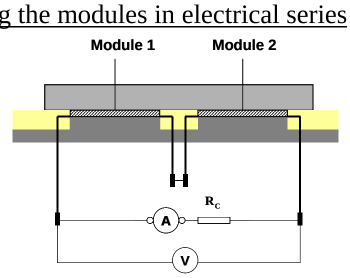


Figure 12. Electrical series connection of both modules

Just in order to probe that TEMs were not damaged after the different test, the support structure was dismounted, a new thermal grease was applied and a new test was performed. This time the modules were connected in electrical series with an electrical load of 0.37 Ω. The electrical power generated by the modules was 26.8 W with ΔT of 200ºC and a temperature at the cold side of 20ºC, power for two modules is in the range indicated by the manufacturer. The results are summarised in table 3.

Module 1-2 in electrical series			Tc≈20ºC ΔT≈200ºC					Type A	
Rc_t=0.37 Ω									
Mod	T_{hi}	T_{ci}	ΔT_i	V	I	Rc_r	P_e	W_e	ε_{e1}
	ºC	ºC	ºC	V	A	Ω	W	W	%
1	219.56	18.81	200.3	3.269	8.20	0.399	26.80	711	3.78
2	218.10	17.75	200.3						

Table 4. Test with the modules connected in series

Conclusions

In this paper a test bench for analysing commercial Seebeck modules has been described. A first prototype has been constructed using commercial materials, trying to minimise its cost. The first results obtained show that the test bench allows for analysing the performance of this type of modules accurately, at least from an engineering point of view. The thermal losses at the heat source and the thermal bypass can be considered negligible, being possible to calculate the energy conversion efficiency as the quotient between the electric power generated by the module and the heat power supplied to the electrical resistors. The results obtained for a commercial module tested in the bench match the nominal values provided by the manufacturer. Therefor this test bench is considered a good tool to design applications where the temperature and power conditions may be different than the nominal. Previously to analyse different modules, the caudalimeter will be changed in order to measure properly the heat dissipated at the cold side. Other insulant materials will be tested for minimising the thermal losses and the support structure will be designed using numerical methods.

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