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THERMOELECTRIC MODULE CHARACTERIZATION

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Abstract

An experimental set-up is described, which permits the measurement of the thermal conductance C and simultaneously the overall Seebeck coefficient S for average module temperatures between 20 and 45°C. Measurements were made on 3 commercial modules of different cross section of thermoelectric material.
The module performances are calculated with the above results and the module's electrical resistance R.
Some direct measurements of the cooling powers, with voltage and electrical current measurements, are made.
A comparison between the manufacturer's performance curves, the calculated performances from the measured values R, S and C and from some direct measurements are given. The results confirm the validity of the method using R, S and C.

1. OBJECTIVE

The performances of thermoelectric modules are given by most manufacturers in the form of charts. Each manufacturer uses its own representation, which is a graphical transcription of the well known equations of thermoelectricity. These charts are generally established using the zero cooling power (corresponding to the maximum available temperature difference) and the zero temperature difference (corresponding to the maximum available cooling power), the intermediate values can be obtained by calculation.
For instance we present here in Fig 1 the representation adopted by MELCOR (990 Spruce Street - Trenton - New Jersey 08648 -USA).
It shows for a fixed hot side temperature T_h, using the current intensity I as a parameter :

a) The voltage V required by the module
b) The cooling power Pc delivred at the cold side as a function of the cold side temperature T_C (or the temperature difference ΔT).

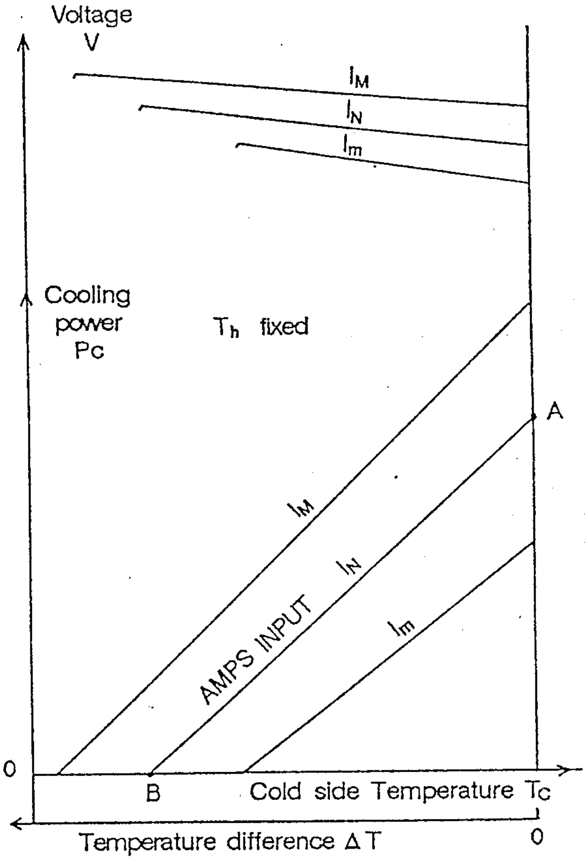


Fig.1. MELCOR's chart for a thermoelectric module.

The curves on this graph are linear functions of T_C because the basic equations are linear and the characteristics R, S and C are linear functions of temperature in the range considered.
For a given current intensity, for instance for I_n nominal intensity, the point A is the point corresponding to the zero temperature difference and the maximum cooling power and the point B is the point corresponding to the maximum temperature difference and a cooling power equal to zero .

I_M is the maximum advisable electrical current, and I_m is the minimum pratical electrical current.

HEYLEN[1] proposed a method for the direct determination of the Figure of Merit of the thermoelectric modules. HEYLEN's method uses two identical modules sandwiched with an electrical heater. To obtain precise results it requires skilful measurements.

We presented in 1984 an apparatus[2] to characterize thermoelectric material and then we designed and built thermoelectric heat fluxmeters[3], which can be used to determine the thermal conductivities of many kinds of materials and the interface thermal resistances of any type of contact between two solid materials.

The objective of the present paper is to use first of all the previous work to determine the performances of thermoelectric modules by measuring their thermal conductance C and then to measure the other characteristics R and S.

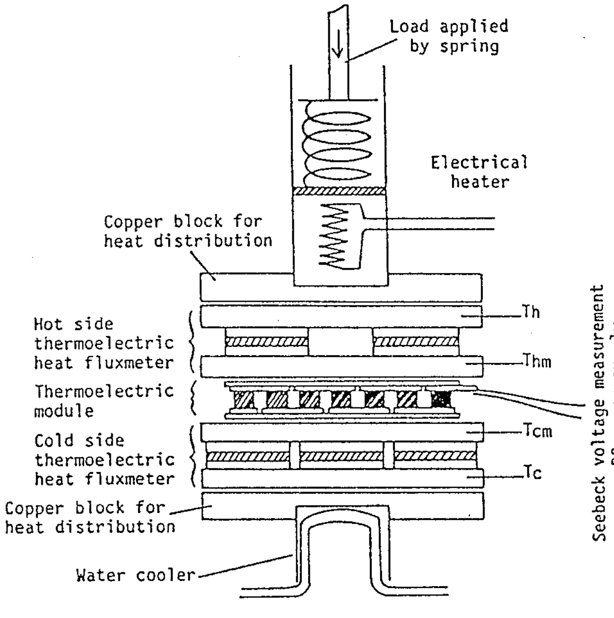
2. DESCRIPTION OF THE EXPERIMENTAL SET-UP

We will first briefly present the thermoelectric heat fluxmeter which is used in the experimental set up.

2.1. Experimental arrangement

In the temperature differential unit[2], that we use for the fluxmeter calibration, the module to be measured is placed between two thermoelectric fluxmeters.

The schematic of this stack is given in Fig. 2.



Indice h stands for hot, C for cold
m for the module

Fig 2. Schematic of the experimental arrangement.

The contact between the external sides of the module and the fluxmeter is made by a thermal compound (Dow Corning G340).

A pressure of the order of several atmospheres is applied by a spring placed in the temperature differencial unit.

From the top to the bottom we find :

- an electrical heater placed under the spring casing
- the hot side thermoelectric fluxmeter
- the thermoelectric module
- the cold side thermoelectric fluxmeter
- a copper bloc with a water cooling circuit.

2.2. Thermoelectric heat fluxmeter

A thermoelectric heat fluxmeter[3] is constituted by several pieces of thermoelectric material placed between two copper plates. For pratical considerations these pieces of thermoelectric material are first soldered between two copper discs (with a nickel layer to avoid the diffusion of copper into the material) and then the pieces with the copper discs are soldered between the two larger copper plates. We chose thermoelectric pieces of 1.5 cm^2 in area, 1.5 mm thick soldered between copper discs of 18 mm in diameter and outer copper plates of 55 X 55 mm with a thickness of 5 mm.

We built two fluxmeters, one with 5 pieces of thermoelectric material, the second with 9 pieces.

A drawing of the two fluxmeters is given in Fig 3.

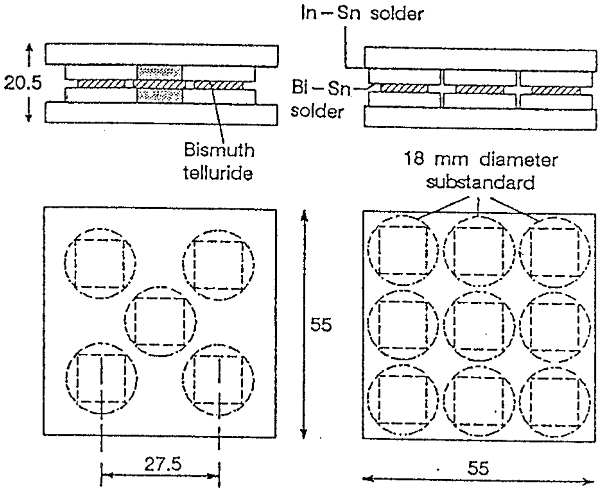


Fig.3. Drawing of the five and nine piece fluxmeters

For each fluxmeter, the thermal conductance was determined by direct calibration, using a standard with a known conductance. This comparative method is done in the temperature differencial unit.

The temperature difference across the fluxmeter generates a voltage, which can be measured and used to calculate the heat flux (thermal power) going through the fluxmeter.

We can write : $V = S.\Delta T$

Where S is the overall Seebeck coefficient.

The thermal conductance C gives the value for the thermal power P.

$P = C.\Delta T$

so $P = (C/S).\Delta V$

The ratio C/S is the fluxmeter constant expressed in W/V.

It is therefore possible with this fluxmeter to know the thermal power either by measuring a temperature difference or a voltage.

2.3. Experimental procedure

The module to be tested is sandwiched between the two thermoelectric fluxmeters with at the interfaces a thin film of a thermal compound (Dow-Corning G340). We use calibrated thermocouples to measure the temperatures T_h, T_{hm}, T_{cm}, T_c, in the plates of the fluxmeters. See Fig 2.

This method gives directly the temperature difference across each fluxmeter. The temperature in each plate of the two fluxmeters facing the thermoelectric module enables one to calculate the module's temperature difference and its average temperature. The temperature difference across the module includes the thermal resistances due to the internal connections and the ceramics. Is is the effective temperature difference of a thermoelectric module.

As in the measurement of the thermal conductivity of a single piece of thermoelectric material[2], the accuracy of temperature measurements can be enhanced by 4 sets of measurements using a permutation of the location of thermocouples.

The measurements can also be made using small diameter platinum resistances (such as 100 ohms at 0°C, the precision exceeds 0.1°).

There are two types of measurements for the thermoelectric module depending whether the electrical current through the module is zero or not.

a/ Determination of characteristics R, S, C

In this case there is no electrical current going through the thermoelectric module. The temperature differential unit imposes a thermal flux between 2 w and 20 w through the whole stack. We assume that the heat losses are negligeable by using an efficient thermal insulation of 12 mm thick (thermal conductivity of 0.04 W/(m.K)) around the stack, the heat loss does not exceed 0.05 w, so we consider that the heat flux is the same along the whole stack. In fact we note always some differences between the two values and we adopt for the heat flux the mean value of these indications, they are within 5 %.

$$P = C_h\ (T_h - T_{hm}) = C_c\ (T_{cm} - T_c)$$

The thermal conductances of the two fluxmeters are :

C_h = 0.673 w/K and C_c = 1.182 w/K.

The thermal conductance of the module C is given by :

$$C = P/(T_{hm} - T_{cm})$$

at the temperature : $T = (T_{hm} + T_{cm})/2$

Simultaneously we measure the generated voltage V of the module and we can calculate :

- the overall Seebeck coefficient for the module

  $S = V/(T_{hm} - T_{cm})$

- the effective Seebeck coefficient for the single thermoelectric element of the thermoelectric module :

  $s = S/n = V/n.(T_{hm} - T_{cm})$

Where n is the number of thermoelectric elements.

The electrical resistance R is measured independently on the module when it is in thermal equilibrium, measurements are made in a controlled enclosure between 20 and 45°C.

The overall Figure of Merit Z can be evaluated using the above values :

$$Z = S^2/(R.C)$$

These values, C, S, R and Z are the effective values of the module.

b/ Direct measurement of cooling power P_C, V and I

In this case an external power supply delivers an electrical current through the thermoelectric module. The electrical current and the voltage drop across the module are measured.

The polarity of the direct current is chosen so that the cold side of the module is facing the electrical heater (at the top of the stack) and the hot face is facing the water cooler (at the bottom of the stack).

A constant current source is connected to the module. At equilibrium, (no heat accumulation along the stack), the thermal powers measured by the two fluxmeters are respectively equal to : 1) the cooling power delivered by the module (equal to the heating power of the electrical heater) 2) to the calorific power of the module (equal to the cooling power of the water

cooler). The experiment requires some skill to adjust the appropriate values of electrical heating and water cooling to obtain the desired level of temperature for the module.
When thermal equilibrium is reached, the 4 temperatures for the two fluxmeters are measured.

3. MODULES TESTED

The modules tested are manufactured by MELCOR. They have alumina ceramic plates.
MELCOR's designation for these modules is the following

CP x-y-z

Where

- x : characterises the size of the thermoelectric element. x in mm is the side of the square cross section and for the largest modules CP5 it is the diameter of rod with an equivalent cross section.
- y : gives the number of couples. The number of single elements n is then 2y.
- z : is the height of element in thousand's of an inch.

We determined the characteristics R, S and C of three modules.
The physical characteristics of the tested modules are summarized in the table below.

	CP1.4-127-06	CP2-71-065	CP5-31-065
size of single thermo-element mm	1.4 x 1.4	2.16 x 2.16	4.44 x 4.44
Cross section A mm^2	1.95	4.67	19.76
Number of couples n =	127 254	71 142	31 62
height of thermo-element h mm	1.651	1.651	1.651
overall size of module (mm)	40 x 40	44 X 44	55 X 55
** h/A m^{-1}	846	354	83.6
thickness mm	3.8	4.6	4.9

The modules were tested under the same pressure of 0.7 ± 0.1 MPa (7 atmospheres) ; in this way the interface resistances between the module and the fluxmeters can be assumed to be the same.

4. EXPERIMENTAL CHARACTERISTICS R, S, C

The results of our measurements on different types of modules are summarized in the following table, which gives the values of the thermoelectric parameters at 27°C (300 K).

Module	Electrical resistance R	Seebeck coefficient S V/K	Thermal conductance C W/K	Figure of Merit $Z \times 10^3 K^{-1}$
CP1.4-127-06	2.1673	0.04813	0.420	2.55
CP2. - 71-06	0.5533	0.02626	0.483	2.58
CP5. - 31-06	0.05729	0.01166	0.961	2.47

The precision on the measurements can be evaluated for R and S ± 1 %, for C ± 5 %, thus for Z ± 7 %.

4.1. Calculation of thermoelectric parameters ρ, s, k, Z

Using the overall measured characteristics R, S and C (at I = 0), it is easy to calculate the effective average thermoelectric material characteristics : *

ρ electrical resistivity Ω.m, $\rho = R . A/(n . h)$

s Seebeck coefficient per element V/K, $s = S/n$,

k thermal conductivity W/(m.K), $k = C.h/(A.n)$

The Seebeck coefficient s is calculated and plotted instead of S.
The measurements are repeated for different values of the mean temperature of the module. This is obtained by varying the power of the heat source.
In Fig. 4 the Seebeck coefficient per element s, the electrical resistance R and the thermal conductance C are plotted for the module CP1.4-127-06 as a function of the average module temperature between 18 and 47°C.

Linear correlation by least mean squares gives the following correlations from experimental data in the temperature range 20 to 45°C :

$$R_t = R_{27} \, (1 + fr \, (t_{av} - 27)) \qquad (1)$$

with fr = 0.0044 ± 0.0005

$$s_t = s_{27} \, (1 + fs \, (t_{av} - 27)) \qquad (2)$$

obviously :

$$S_t = S_{27} \, (1 + fs \, (t_{av} - 27))$$

The coefficient fs is the same for the three modules tested : fs = 0.0015 ± 0.00006.

$$C_t = C_{27} \, (1 + fc \, (t_{av} - 27)) \qquad (3)$$

The thermal condutance C remains approximately constant fc = 0 ± 0.0002 and we adopt a constant value (fc = 0).

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** : Values given by Melcor

* see page 6.

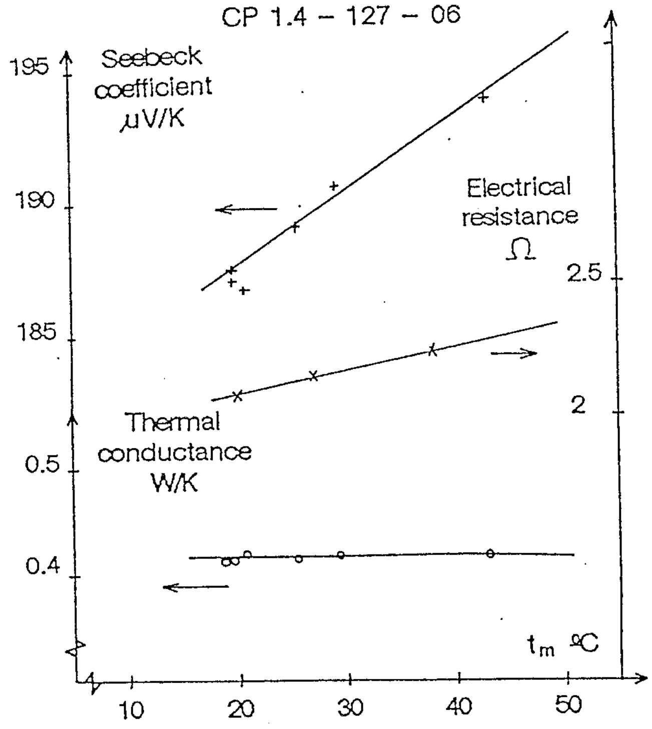

Fig 4. Seebeck coefficient, electrical resistance and thermal conductance as a function of the average module temperature.

4.2. Calculated values (powers and voltage)

The values are calculated with the classic formulas :

$P_c = S.I.T_c - 1/2\ R.I^2 - C\ (T_h - T_c)$

$P_h = S.I.T_h + 1/2\ R.I^2 - C\ (T_h - T_c)$

$P_E = S.I.(T_h - T_c) + R.I^2.$

$V = S.(T_h - T_c) + R.I$

Where :

R, S and C are obtained from equations (1),(2),(3).
The temperatures T_{hm} and T_{cm} are those of copper plates pressed against the module's ceramics with a thermal grease and under a pressure of 0.7 MPa. For constant current values at T_{hm} = constant, the functions P_c, P_h, P_E and I are linear functions of T_{cm} and ΔT. These linear functions are really only valid in the temperature range of 20 to 45°C, where the characteristics R, S and C were measured ; we have extended these lines.

5. DIRECT COOLING POWER AND ELECTRICAL MEASUREMENTS

It is wise in experimental work, when it is possible, to make redundant measurements and to cross check ; in this case the set-up permitted the direct measurement of the cooling power, voltage and electrical current. These experimental results for module CP 1.4-127-06 are represented by small circles (o) in Fig. 5.
Only the cooling power P_C and the voltage $V = P_E/I$ are on this graph.
Valid experimental results require that :

$P_h = P_C + P_E$

In our experimental work the discrepancy in the energy balance sometimes exceeded 10 %, because the temperature differential unit lacked cooling power for the larger modules tested.

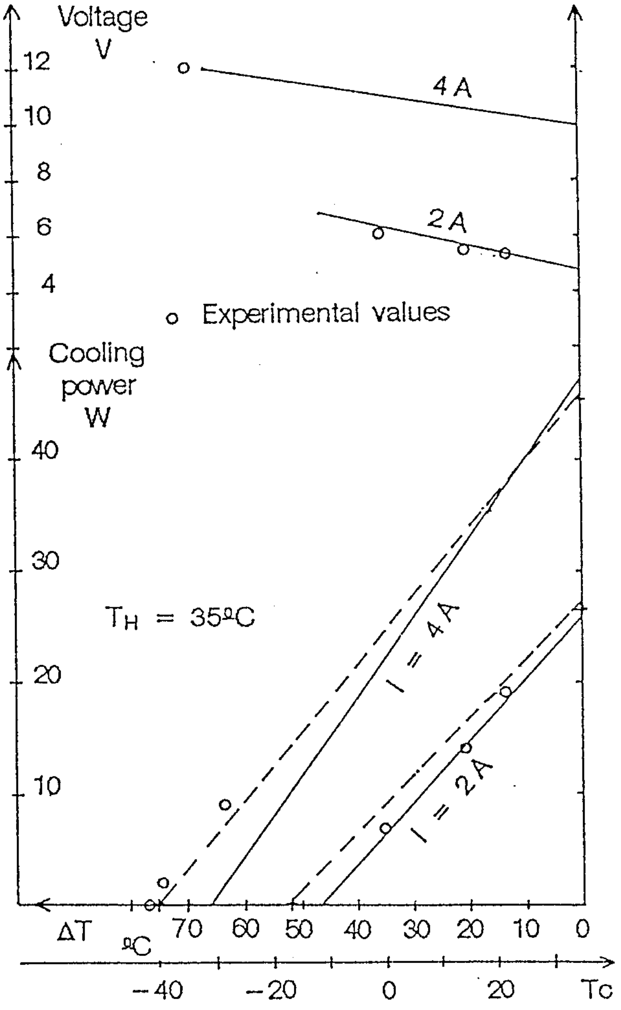

Fig. 5. Module MELCOR CP1.4-127-06
Comparison of manufacturer's curves (———), curves calculated from measurements of characteristics (– – – –) and directly measured values (o).

6. ESTIMATED ACCURACY

The measurements, at I = 0, of the thermoelectric module's characteristics R, S and C, as a function of temperature, enable the calculation of the module's performances.
Direct measurements are made, at constant current, of the cooling power P_C and voltage V. These measurements included the heating power, but the energy

balances were poor with errors of 10 % and an error in the cooling powers of ± 2 W. These measurements only confirmed the accuracy of the calculated powers from R, S and C of ± 10 %, we believe that in fact the accuracy of this method is probably slightly better than this, but extensive measurements are required.

The modules perform slightly better than the values indicated by the manufacturer's curves. The manufacturer's curves correspond to average (or minimum) values so this difference does not affect the estimated accuracy.

7. CONCLUSION

A relatively simple method to mesure the three fundamental parameters of a module R, S and C has been presented. These parameters are necessary for thermal modelling of thermoelectric systems - either for heat pumps or electricity generation - that use modules.

The cooling and electrical powers of a commercial module have been calculated using the basic thermoelectric equations. Direct measurements of the cooling power, voltage and electrical current confirm within 10 % the validity of the proposed method.

The cooling powers were found to be slightly above the manufacturer's curves.

ACKNOWLEDGMENTS

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NOMENCLATURE

Symbol	Unit	
A	m^2	cross section
C	W/K	thermal conductance
I	A	electrical current
k	W/A(m.K)	thermal conductivity
n	-	number of thermoelectric elements
P	W	power
R	Ω	electrical resistance
s	V/K	Seebeck coefficient of thermoelectric element
S	V/K	Overall Seebeck coefficient of the module
T	K	temperature
ΔT	K	temperature difference
V	V	voltage
Z	K^{-1}	Figure of Merit
ρ	Ω.m	electrical resistivity
Indices		
av		average
c		cold
E		electrical
h		hot
m		module

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* Material properties calculated from module measurement

	units	CP1.4-127-06	CP2-71-06	CP5-31-06
ρ	μΩ*m	10.09	11.01	11.05
S	μV/k	189.5	184.9	188.1
k	W/(m*K)	1.40	1.20	1.30
Z	K^{-1}	$2.55\ 10^{-3}$	2.58×10^{-3}	2.46×10^{-3}

temperature = 27°C