MEASURING METHODS OF THERMOELECTRIC COOLERS NON-STATIONARY DYNAMICS IN Z-METERING

L.Yershova[1], I.Drabkin[2], V.Volodin[1], D.Kondratiev[1]

[1]Institute of Physics and High Technologies, Moscow, Russia
[2]Institute of Chemical Microelectronics Problems, Moscow, Russia
Fax: +7-095-132-5870

1. Introduction

Temporal characteristics of a thermoelectric cooler (TEC) are important performance parameters for any device involving TEC. In paper [1]a single thermoelectric pellet non-stationary processes in the so-called regular mode [2] were studied and the obtained formulae were generalized for one-stage TECs loaded by various heat to be pumped. In paper [3] there are derived expressions for the time constant of single-, two- and multi-stage TECs. This paper studies transient processes concerned in Figure-of-Merit measurements with the Z-meter. It compares experimental and theoretical [3] results and yields the evaluating approach for obtaining relaxation time values in real thermoelectric devices.

2. TEC Time Constant Theory

Let us define the time constant as the period enough for the temperature difference between the initial and stationary states decreases e-proportionally. In paper [3] corresponding differential equations are solved and maximum time constants for the slowest exponential processes are found. The thermoelectric cooler (TEC) electrical current limit is as follows:

$$j << \frac{\alpha L}{\kappa_0}, \tag{1a}$$

where j – the current density, α – the Seebeck coefficient, κ_0 – the average n/p pellets thermal conductivity, L – pellets height. Eq. (1) means the TEC current must be much lower than the maximum module current Imax, that is the current at which the TEC yields the highest temperature difference at zero heat load:

$$I << I_{max}, \tag{1b}$$

Designate the slowest expo-process as τ_{max}. There are certain cases when this value is defined.

1) One-stage TEC, its hot side temperature constant and cold side adiabatically isolated:

$$\tau_{max} = \frac{LC_1}{\left(1 + \frac{L\alpha j}{\kappa_0}\right) s_0 \kappa_0 N}, \tag{2}$$

where C_1 is the heat capacity of cold side junctions, substrate and objects to be cooled; N is the module pellets number, s_0 – a pellet cross-section.

2) One-stage TEC, its substrates in free heat exchange with the medium (free TEC):

$$\tau_{max} = \frac{C_1 C_2 L}{(C_1 + C_2)\kappa_0 N s_0}, \tag{3}$$

where C_1, C_2, are the heat capacities of all the elements on the cold and hot substrates.

Eq. (3) is the maximum time constant at j=0. When $j \neq 0$ the time constant is to be found via numerical solution of the corresponding characteristic equation.

For the free module case this time is approximately twice lower than for the one with the thermally stabilized hot side, see (2).

3) Two-stage TEC, its hot side temperature constant and cold side adiabatically isolated. For this variant two exponential processes – slow and fast – manifest themselves. Their time constants are:

$$\tau_{max} \approx \tau_{1max} + \tau_{2max}, \tag{4a}$$

$$\tau = \frac{\tau_{max1}\tau_{max2}}{(\tau_{max1} + \tau_{max2})} \tag{4b}$$

Here τ_{1max} and τ_{2max} are time constants of the one-stage TECs formed by each cascade.

Therefore for an n-stage TEC time constant can be expressed as the sum of the each cascade times and all possible combinations like that in (4b):

$$\tau_{max} \approx \tau_1 + \tau_2 + \ldots + \tau_n, \tag{5a}$$

$$\tau_{ij} = \frac{\tau_{max\,i}\tau_{max\,j}}{(\tau_{max\,i} + \tau_{max\,j})} \;\forall\; i, j \tag{5b}$$

3. Time Constant Measurement

The Device DX3065 allows measuring the parameters of a TEC both in the air and while effective heat rejection from the TEC hot side is carried out, i.e. for the TEC mounted onto some heat sink.

The function of the device is double. On the one hand, it enables testing the TEC Figure-of-Merit by the Harman method; on the other hand, it telemetrically tracks the kinetics of the TEC transfer to the stationary state, for it is this state the Harman method can be applied to. So, one device is not only Z-meter but also τ-meter. The accompanying software allows observing the kinetics data by measuring the temporal behaviour of Seebeck voltage $U_\alpha(t)$ and interpolating the data by the exponent:

$$U_\alpha(t) = Ust_\alpha(1 - e^{-t/\tau}), \tag{6}$$

where Ust_α - the stationary Seebeck voltage, and τ - TEC time constant.

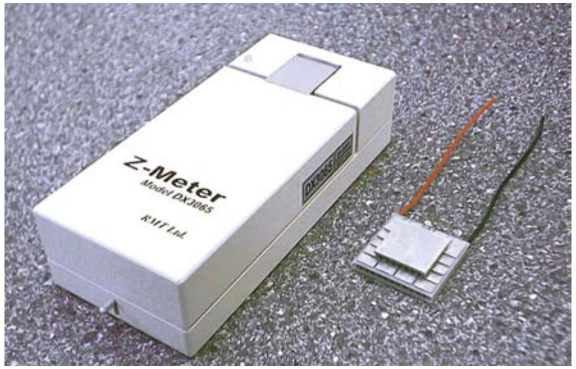

Fig. 1. Z-meter exterior

For checking if approximating the kinetics by a single exponent is correct additional study in the semi-logarithmic scale is possible:

$$f(t) = ln\left(\frac{Ust_\alpha - U(t)}{Ust_\alpha}\right), \tag{7}$$

4. One-stage TEC: Experiment and Theory

Here there are experimental and theoretical [3] data for one-stage TECs both in the free substrates option and with the hot sides thermally stabilized. Denote I for the electric current, τ_{exp}, τ_{theory} for the measured and calculated time constants, D for dimensionless root-mean-square declination, normalized to the stationary Seebeck voltage. In the calculations hereafter the following parameters are used: thermoelectric material heat capacity 0.13 J/g, density 7.5 g/cm^3, the corresponding ceramics values are 0,8 J/g and 3,5 g/cm^3, for the solders – 0,17 J/g and 9,3 g/cm^3, the ceramics is 0.5mm thick.

Table 1.
TECs measured parameters

TEC Type	Substrate sizes, mm^2		s_0, mm^2	L, mm	N	Imax, A
	Cold	Hot				
1MT03-004-13	2,0x1,0	2,3x2,3	0,09	1,3	8	0,3
1MC04-032-15	6,4x6,4	6,4x8,0	0,16	1,5	64	0,5
1MC06-030-05	8,2x8,2	8,2x8,2	0,36	0,5	60	3,2
1MC06-060-05	10,0x12,0	12,0x12,0	0,36	0,5	120	3,2
1MC06-018-15	6,0x6,0	6,0x8,0	0,36	1,55	36	1,1
1MC06-024-15	8,0x8,0	8,0x8,0	0,36	1,55	48	1,1
1MT04-059-16	8,0x7,0	8,0x7,0	0,16	1,6	118	0,45

Experiment and theory were taken at two current values 5mA and 25 mA. Table 1 shows that these currents satisfy the requirement (1b).

Table 2.
Measured and calculated one-stage free-substrated TECs time constants

TEC Type	I, mA	τ_{theory}, s	τ_{exp}, s	D
1MT03-004-13	5	1.92	2.43	0.0018
	25	2.87	2.55	0.0007
1MC04-032-15*	5	2.56	3.20	0.0003
	25	3.53	3.14	0.0001
1MC06-030-05*	5	0.82	0.75	0.0012
	25	0.82	0.71	0.0003
1MC06-060-05	5	0.80	0.68	0.0009
	25	0.80	0.65	0.0002
1MC06-018-15*	5	2.56	2.23	0.0007
	25	2.57	2.26	0.0002
1MC06-024-15	5	2.56	2.44	0.0005
	25	2.95	2.47	0.0002
1MT04-059-16	5	2.91	2.47	0.0002
	25	2.91	2.50	0.0001

The sign «*» in Table 2 marks TECs, tested also on the heat sink – see Table 3.

Table 3
Measured and calculated time constants of the one-stage TECs mounted on the heat sink

TEC Type	I, mA	τ_{theory}, s	τ_{exp}, s	D
1MC04-032-15*	5	6.59	6.10	0.0057
	25	6.43	5.77	0.0098
1MC06-030-05*	5	1.65	1.28	0.0036
	25	1.64	1.45	0.0062
1MC06-018-15*	5	4.77	3.96	0.0049
	25	4.71	3.96	0.0071

Table 3 proves that calculated time constants are mainly 10 – 20 % higher than the tested ones. This may be explained by the heat exchange with the environment being allowed for not accurately enough. These processes are apt to diminish time constant. It is also seen that time constants for the free module are nearly twice lower than those for the modules on the heat sinks.

Typical telemetric data are given in Fig. 2.

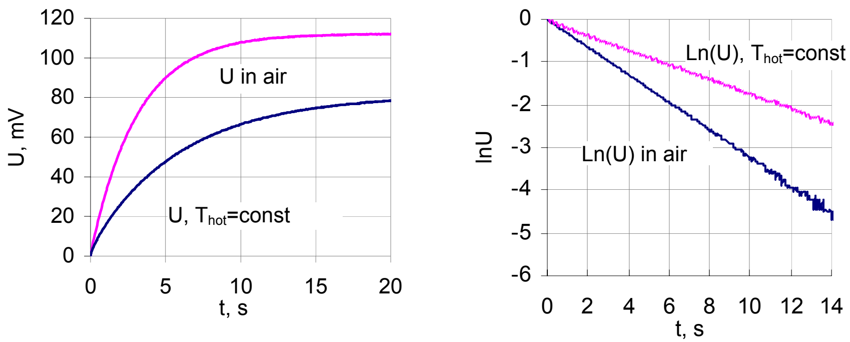

Fig. 2. Measured Seebeck voltage values for the TEC 1MC04-032-15 at 25mA

The data in the logarithmic scale depend on time linearly. Corresponding time constants found from the linear approximation yield 3s and 5.5s, which is agreeable with the results of Tables 2, 3. It is clear that one-stage TEC kinetics is covered by single characteristic time.

5. Two- and Three-stage TECs: Experiment and Theory

The calculations for the multi-stage TECs were only taken at 5 mA and only for the thermally stabilized hot sides. Measurements were carried out at 5 mA both for this very case and for the free modules. The parameters of the tested two-stage TECs are in Table 4.

Table 4.
The two-stage TECs parameters

TEC Type	Substrate sizes, mm^2			s_0, mm^2	l, mm	N_1	N_2	Imax, A
	Cold	Medium	Hot					
2MC06-10-10	3,2x3,2	4,0x4,0	4,0x4,0	0,36	1,05	6	14	1,3
2MC04-039-15	4,9x4,9	6,5x6,5	6,5x6,5	0,16	1,55	36	42	0,3

Here are the calculations results.

Table 5.
Calculated time constants of the two-stage TECs mounted on the heat sink

TEC Type	τ_1, s	τ_2, s	$\tau_1+\tau_2$, s	$\tau_1\tau_2/(\tau_1+\tau_2)$, s
2MC06-10-10	5.04	3.53	8.57	2.07
2MC04-039-15	6.83	9.80	16.63	4.02

We see that the temporal relaxation for two-cascade modules reveal a fast and slow components. So a single exponent approximation is only admitted as a sort of estimation. To what extent is it acceptable? In Table 7 the experimental results are given.

Table 7.
Experimental time constants for the two-stage TEC

TEC Type	Free Module		Mounted Module	
	τ_{exp}, c	D	τ_{exp}, c	D
2MC06-10-10	3.1	0.0012	5.02	0.0011
2MC04-039-15	9.3	0.0007	12.5	0.0001

Consider time behaviour of 2MC04-039-15. Fig. 3 depicts the Seebeck voltage dynamics for two heat exchange variants.

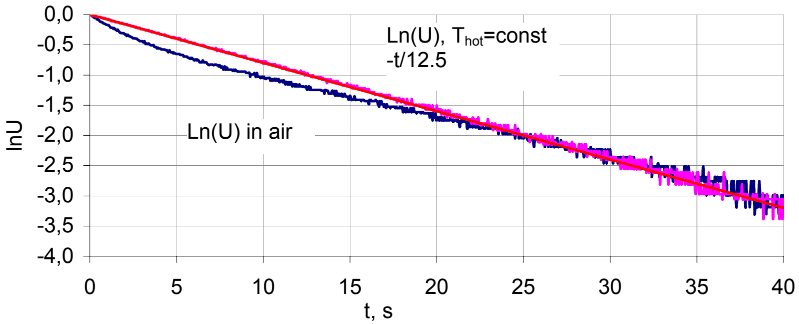

Fig. 3. 2MC04-039-15 dynamics for two heat exchange variants

It is seen that for the mounted option the logarithm has a linear character. Fig. 4 discovers the same TEC dynamics in the free option.

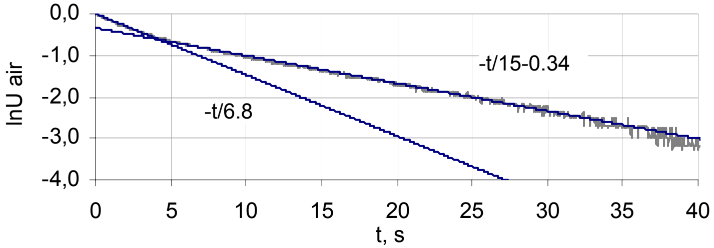

Fig. 4. Logarithmic time behaviour for 2MC04-039-15 in the free heat exchange option at 5mA

Time constants defined in the semi-logarithmic scale are τ =15s и τ=6.8 s, which is quite close to the calculated results of Table 5.

The study for the three-stage TECs is simular. The parameters of the three-stage TECs and the theory results can be found in Tables 8 and 9.

Table 8.

TEC type	Substrate sizes, mm^2			s_0, mm^2	l, mm	N_1	N_2	N_3	Imax, A
	Cold	Medium	Hot						
3MC06-024-13	2.5x2.5	4,0x4,0, 6.1x6.1	6.1x6.1	0.36	1.3	6	14	32	1.05
3MC07-098-115	8x8	10x10, 12x12	12x12	0.49	1.15	36	42	132	1.45

Table 9.
Calculated time constants of the three-stage TECs mounted on the heat sink

TEC Type	τ_1, s	τ_2, s	τ_3, s	$\tau_1+\tau_2+\tau_3$, s
3MC06-024-13	6.11	5.32	4.73	16.16
3MC07-098-115	9.54	5.32	3.08	17.94

In the three-cascade case except the slow evolution described by the summed time constant there are three faster transitory processes referring to (5b). The averaged experimental data on a single exponent regression are offered in Table 10.

Table 10.
Measured results for the three-stage TECs

TEC type	Free Module		Mounted Module	
	τ_{exp}, s	D	τ_{exp}, s	D
3MC06-024-13	5.9	0.0009	11.2	0.0005
3MC07-098-115	4.1	0.0006	8.7	0.0003

Both TECs are very sensitive to the environmental change on the hot side. The reason may be a high cascading coefficient for both these modules (see the similar case for 2MC06-10-10, Table7).

Below there are time behaviour pictures for the TEC 3MC06-024-13. In Fig. 5 one sees the dynamics for two heat exchange variants.

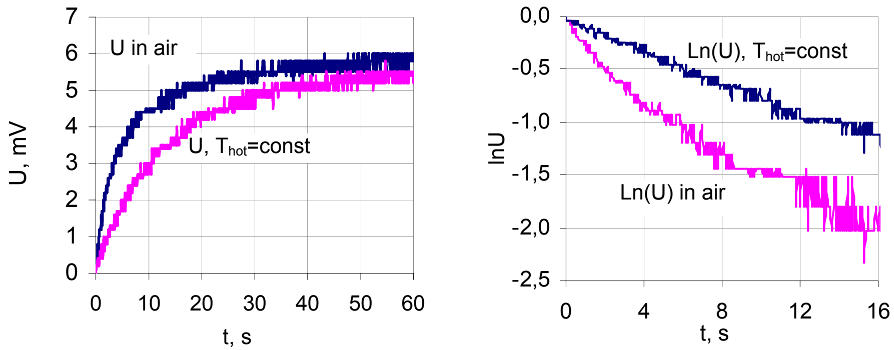

Fig. 5. Measured Seebeck voltage dynamics for the TEC 3MC06-024-13 at 5 mA

The logic found out on the two-stage option remains fair. It is illustrated by Fig. 6.

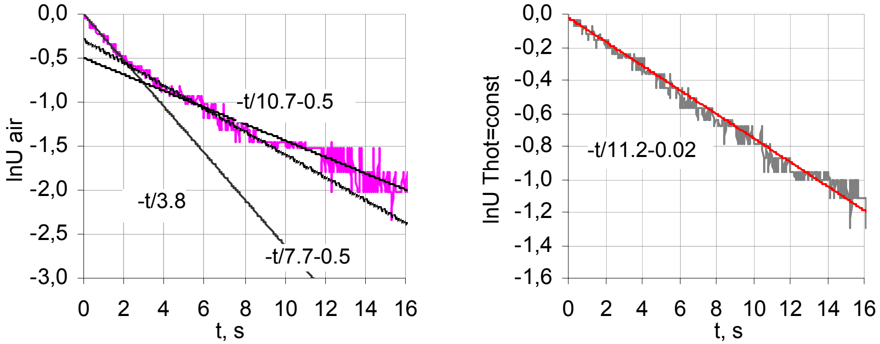

Fig. 6. Logarithmic time behaviour for 3MC06-024-13 for the free heat exchange and mounted options at 5mA.

Fig. 5 convinces one of the fast component presence in the free module testing. This can be captured by the kink of the curve in the semi-logarithmic scale.

The three-cascade case reveals at least three linear curve parts corresponding to different time constants. Comparison of the theory and experiment shows that the tested values are some 30 % lower than the calculated ones, which is no wonder if taking into account the one-stage preceding disagreement.

Conclusion

With the help of the Z-meter DX3065 it is possible to study the process of TECs transfer to the stationary state both in the free heat exchange option (standard Z-meter configuration) and in real performance conditions for modules mounted on the headers, heat sinks, in devices, etc.

Comparison of the theory and experiment shows that the tested values are 10 – 30 % lower than the theoretically predicted figures. However the theory correctly catches the basic relaxation characteristics of TECs as dependent on their real operational-environmental conditions.

Time constants evaluated by Z-meter allow more accurately describing non-stationary kinetics in real thermoelectric devices.

1. E.I.Astakhova, V.P.Babin, U.I.Ravich. Calculation and Measurement of the Cooling Thermoelement in the Regular Mode. Eng.Phys.J., 62, 1992, 284.
2. G.M. Kondratiev. Regular Thermal Mode. Moscow, GITTL, 1954, 408.
3. I.A. Drabkin. Transient Processes in Thermoelectric Cooling Modules and Devices. (Ibid)