Complex Express TEC Testing

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Abstract

For express Thermoelectric Coolers (TEC) control in manufacturing and application, electrical resistance (R) and Figure-of-Merit (Z) measurement is widely spread. In the paper it is shown that there are TEC damage or defect instances not covered by one-parameter testing (R) and even two-parameter testing (R,Z). We offer a three-parameter approach to control TEC's quality: by measuring TEC electrical resistance (R), Figure-of-Merit (Z) and time constant (τ). This method provides possibilities to diagnose TEC defect, which is of vital concern for technology and operational conditions correction. The paper yields theoretical and experimental results proving it. The experimental check is provided with the help of the original testing device R,Z,τ-meter DX3065.

Introduction

Thermoelectric cooling modules are high technology multi-component products having a niche market where reliability is the first significance. The tendency to TEC miniaturizing emphasizes it even more. To meet exclusive reliability, a trustworthy control should be imposed at the final Manufacturer's assembling level (qualification and screening tests) as well as at the incoming and/or operational User's level. That is why if a TEC is faulty, it so important not only to reject the product but, if probable, to define what is specifically wrong with it.

The description of TE material quality by the *three* parameters combination $Z=\alpha^2\sigma/\kappa$ (α – the Seebeck coefficient, κ – thermal conductivity, ρ – electrical resistivity) means some code. If Z is comparatively low, that only tells us the material is not proper – the reason of its degradation is veiled. If measuring along with Figure-of-Merit one or two of three values α, k, R, we become less blind. The same concerns a more complicated system - an assembled TEC. If testing by some separated parameter (only Z or only R, or even both) we may not find out the true problem with the TEC. It is very much like a disease. The best way to treat it is to know the reason. The more complicated the studied system, the more various parameters are to be considered to make a diagnose. For multistage TECs measuring Z is only a rough estimation and the demand for additional criteria is really drastic. We offer TEC testing method by combination of *three* parameters:

1) Electrical resistance (R),

2) Figure-of-Merit (Z) [1],

3) Time constant (τ) [2,3] (defines the time period necessary for a module to reach the steady state in response to the switching of the current).

This has its background. The value R is related to electrics, Z – to thermoelectrics, τ – to thermal physics, namely to thermal conductance of a system. The calculations of R, Z, τ sensitivity to various TEC damages and experimental check of it were carried out with the help of earlier results [4,5,6,7].

The following sections are organized according to TEC specific defects. The technological effects are prioritized. The sections present calculated results on R, Z, τ changing in defected TECs and data measured for modeled cases. The conclusion reduces the results to a diagnostic matrix.

Detachment of Metal Junctions from Ceramics

The parameters R and Z stay almost constant when detachment of metal junctions from ceramics occurs. The only value considerably sensitive to the defect is the TEC time constant. With basis [5] it may be shown that if metal junctions of *n* pellets in *N*-pellet TEC are detached, τ grows as

$$\tau \cong \frac{\tau_{nom}}{(1-\frac{n}{N})}, \tag{1}$$

Here and after index "nom" is referred the faulty TEC time constant. In case n is very close to *N*, time constant of separate pellets may appear. The latter is nearly one order of magnitude lower than that of the module [5].

In Fig. 1 the behavior (1) is presented in relative values.

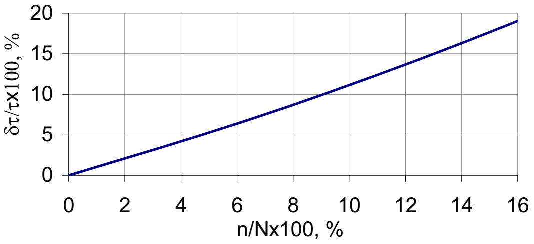

Figure 1: *Time constant dependence on the relative ratio of the metal junctions detached from the ceramic substrate.*

Commonly the case *n*<<*N* is of practical interest. So, it is this approximation that we study further.

Confused p-n pellets polarity

We consider this problem supposing the absolute values of TE parameters of p- and n-types of the pellets material are the same. In this approach TEC resistance remains unchanged.

Based on the equations [6,7] for *n* confused pellets we get:

$$Z = Z_{nom}\left(1-\frac{n}{N}\right)^2 \tag{2}$$

In Fig. 2 this case is depicted in relative values.

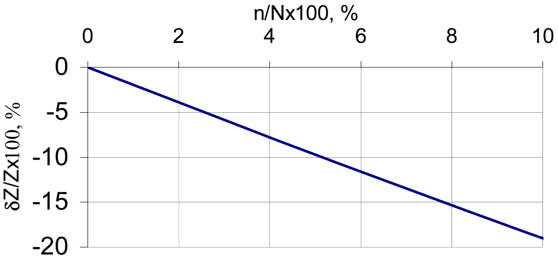

Figure 2: *Figure-of-Merit dependence on the relative ratio of the confused pellets.*

With grounding [5] it may be calculated that τ grows as a function of ratio *n/N*. This increase is more considerable with higher electrical current: It means that in the Harman method [1], at very small current, the dependence is negligible.

In Fig. 3 we present the relative values behavior.

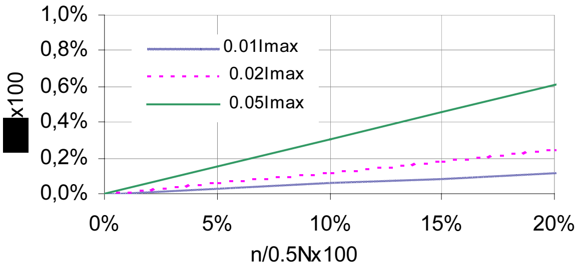

Figure 3: *Time constant dependence on the relative number of confused pellets at different current values*

The experiment was carried out on two TEC lots with different unequal n- and p- pellet numbers. In Figure 4 and Table 1 we present the picture of R, Z, τ changing in comparison to the nominal case.

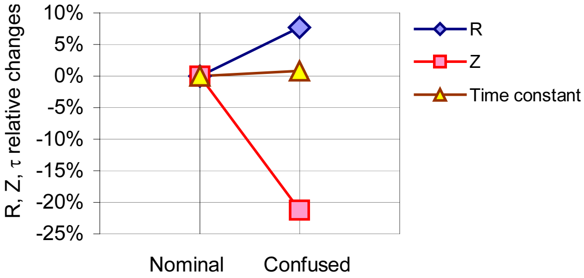

Figure 4: *Experimental data on average relative changes of R, Z, τ for TECs with confused pellets polarity (Lot 1)*

As shown, Figure-of-Merit is the most sensitive as predicted by theory. We believe R varies due to the difference of p- and n- materials resistivity. Table 1 gives the corresponding to Fig. 4 numeric comparison.

Table 1. *Measured Z, R, τ relative changes (Lot 1)*

δR/R	δZ/Z	δτ/τ
7.7%	-21.2%	0.8%

Table 2 offers the experimental and theoretical relative Z decrease (Lot 2). We see that the calculated values in average 5% underestimate the effect. Probably it is due to some disagreement of p- and n- types TE material properties neglected in theory.

Table 2. *Experiment and theory comparison (Lot 2)*

n/Nx100	$\delta Z/Z_{exp}$	$\delta Z/Z_{calc}$
4.2%	-11.7%	-8.2%
8.3%	-20.4%	-16.0%
15.8%	-36.2%	-29.2%

Thermal and Electric Contact of Pellet Wall and Solder Meniscus

Thermal and electrical conductivities of the solder are higher than those of TE material (Table 3).

Table 3. *Solder and TE material properties comparison*

Material	Electrical Conductivity, $Ohm^{-1}\cdot cm^{-1}$	Thermal Conductivity, W/m·K
TE material	10^3	1.45
PbSn Solder (60:40)	$7.1\cdot10^4$	50

Pellet wall-solder contact may considerably affect TEC efficiency parameters.

This results in effective modifying of pellet thermal conductance or both thermal conductance and electrical resistance. In Fig. 5 we differentiate two cases: non-wetting (1) and wetting (2).

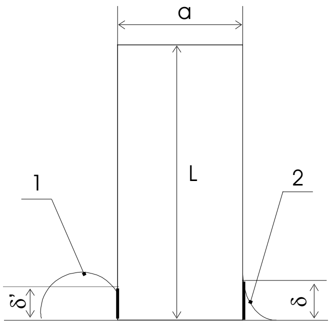

Figure 5: *Non-wetting (1) and wetting (2) solder menisci rough model*

1) Non-wetting.

Only thermal contact appears. The thermal contact area height δ' is usually smaller than that in Fig. 5. If *L* and *a* are pellet height and cross section dimension, Z and τ values are estimated as in Eq (3).

$$Z,\tau = \frac{Z_{nom},\tau_{nom}}{1+\dfrac{4\delta'^2}{a(L-\delta')}}\ ,\ R=const \qquad (3)$$

The greater *L*, the less noticeable the effect (see Fig. 6, 7).

2) Wetting

It is a more common and detrimental case because it shunts a part of pellet not only thermally but also electrically and the contact area height δ is larger than in case 1. Effectively thermal conductance and electrical resistance change in antiphase and that means the following:

$$R,\tau = \frac{R_{nom},\tau_{nom}}{1+\dfrac{4\delta^2}{a(L-\delta)}}\ ,\ Z=const \qquad (4)$$

In Fig. 7 we give a comparative calculation of τ change in two cases.

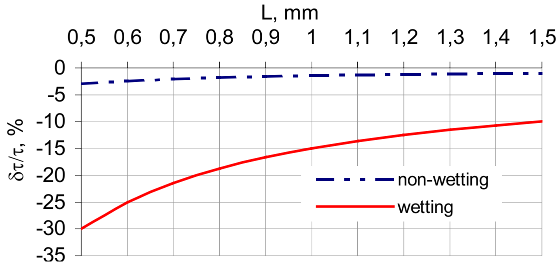

Figure 6: *Time constant change vs pellet height at non-wetting (δ' =0.045mm) and wetting (δ =0.15mm); a=0.6mm.*

The decreasing of TEC time constant is characteristic of this effect. In Fig. 7 and Table 4 the experimental results on the TEC with pellet 0.5 and 1.5 mm are presented.

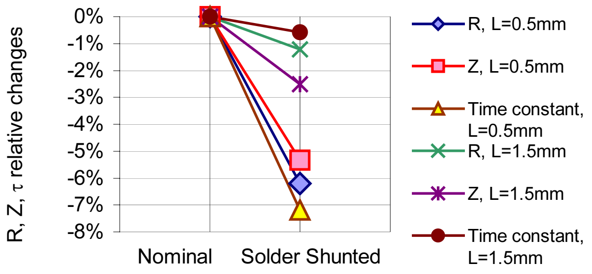

Figure 7: *Experimental data on average relative changes of R, Z, τ for TECs with pellets walls solder-wetted*

Table 4. *Numerical data and theoretical results (Fig. 7).*

L, mm	a, mm	Experiment			Theory X:Z,R,τ
		δR/R	δZ/Z	δτ/τ	δX/X, δ=0.08mm
0.5	0.6	-6.2%	-5.3%	-7.2%	9.2%
1.5	0.6	-1.2%	-2.5%	-0.6%	2.9%

Simultaneous decrease of all the three parameters values means we deal with some mixture of case 1 and 2 in experiment, so, in calculations we used (3) and (4) excepting constants with common average δ=0.08mm. The parameters changes are heavier with pellet smaller height (L).

TEC Pellets Short Circuit

If *n* is the number of short-circuited pellets, TEC electrical resistance and Figure-of- Merit drop linearly with *n/N*:

$$R,Z=(1-\frac{n}{N})R_{nom},Z_{nom} \qquad (5)$$

So, the relative changes dependence is calculated like this:

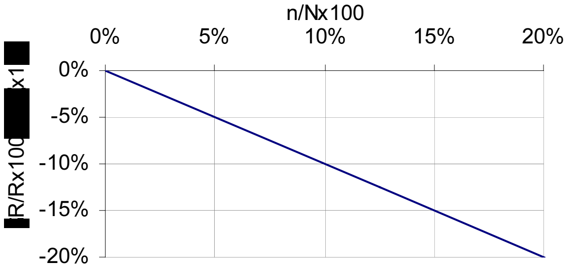

Figure 8: *Calculated R and Z behavior for TECs with n short circuit pellets*

In calculating the time constant behavior we simulate the module as a working part of the good TEC and a thermal shunt consisting of short-circuited pellets and the substrates portion attached to them. Basing on [5] we have τ drop:

$$\tau \cong \frac{\tau_{nom}}{(1+\frac{n}{N})}, \qquad (6)$$

In Fig. 8 and Table 5 we give the experimental results on the TEC with 0, 20 and 40% short-circuited pellets.

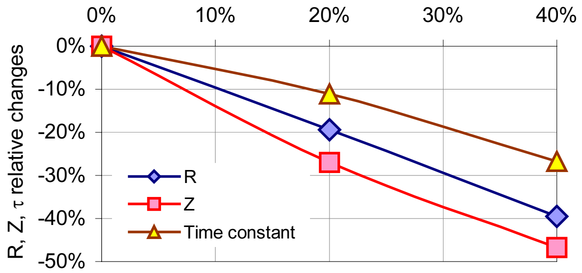

Figure 8: *Experimental data on average relative changes of R, Z, τ for TECs with short-circuited pellets*

Table 5. *Experimental / calculated data for Fig. 8 case.*

n/N	Experiment			Theory		
	δR/R	δZ/Z	δτ/τ	δR/R	δZ/Z	δτ/τ
20%	-19.4%	-27.0%	-11.1%	20.0%	20.0%	16.7%
40%	-39.5%	-46.8%	-26.8%	40.0%	40.0%	28.6%

We consider experiment confirmation satisfactory. Z underestimation may be referred to not taking into account effective increase of thermal conductance due to shunting in Z calculations.

Two-stage TEC: Confused Stage Polarity

In comparison with common concepts, we offer TEC time constant as a new parameter to measure. There is another very demonstrative example of how it is useful.

In a two-stage TEC with confused stages polarity we have unchanged electrical resistance. Figure-of-Merit (to the extent the two-stage case can be estimated in the Harman methodology) is also insensitive criterion.

In the correct polarity case the maximum two-stage TEC time constant equals the sum of time constants of its separate stages [5]. In the confused polarity case two stages work for one substrate. That means quite an abrupt drop of τ.

For one of our two-stage TECs assembled correctly we calculate[5] τ=5.3s. For one stage inverted the theory gives 2.9s. In Fig. 9 the experimental results on the TECs correct and inverted are presented.

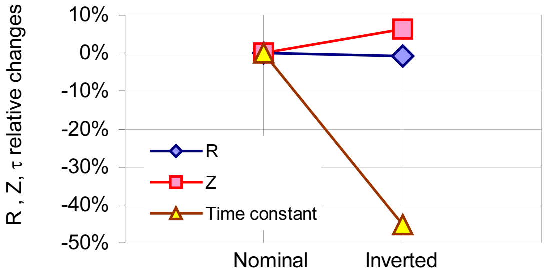

Figure 9: *Experimental data on average relative changes of R, Z, τ for 2-tage TECs correct and inverted*

The experiment confirms that the time constant measurement is of first-rate significance here.

Material Degradation

Let's consider a mechanical kind of TE material degradation, for example microcracks. As our testing experience says, usually at this defect electrical TEC resistance grows. Agreeing with this Figure-of-Merit decreases. The time constant value appears less sensitive to the effect as it represents a more fundamental parameter – thermal conductance.

In Fig. 10 we offer the experimental dynamics of measurement data on TEC exposed to thermal cycles and suffering from progressing microcracks.

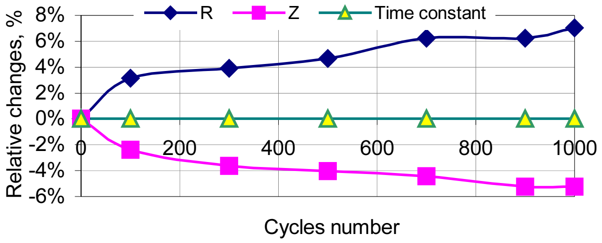

Figure 10: *Experimental data on relative changes of R, Z, τ of TEC with TE material degraded mechanically*

A more complex material degradation takes place at high temperature operation and current load. In Fig. 11 experimental dynamics of TEC parameters during burn-in testing is presented.

Degradation of TE module is demonstrated by corresponding raise of R and fault of Z. Time constant also has tendency to change.

Obviously, at the condition of burn-in testing (both high temperature and maximal current operation at cycling) degradation is a sum of several mechanisms. The example of the testing data is shown below.

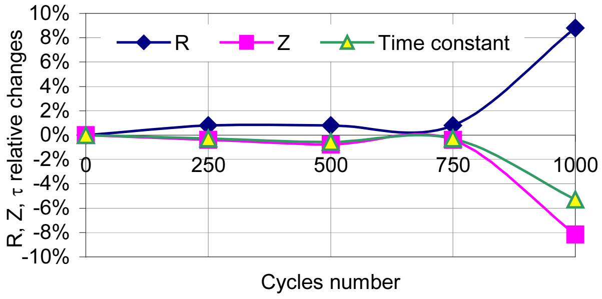

Figure 11: *Experiment data on relative changes of R, Z, τ of TEC with TE material degraded during burn-in testing*

Conclusions

TEC control based on the measurement of three parameters R, Z, τ allows more accurate diagnostics of various TEC defects. It is summed and illustrated by Table 6.

With the help of this diagnostics matrix one can see that the parameter R only picks out 3 cases from 7. Both R and Z give quite a more detailed picture enabling to *diagnose* 4 cases out of 7. But cases 2 and 3a are still overlapped.

All the considered defects variants are successfully differentiated by measuring the behavior of TEC time constant τ along with electrical resistance R and Figure-of-Merit Z.

This diagnostics is useful at typical tests as it enables to identify some hidden defects and injuries and timely eliminate them.

Table 6. *TEC defects diagnostics matrix*

Defect	R	Z	τ
1. Metal junctions detachment	~const	~const	↑
2. Confused p-n pellets polarity	~const	↓	↑ *
3a. Thermal Contact of Pellet Wall and Solder Meniscus	~const	↓	↓
3b. Thermal and Electric Contact of Pellet Wall and Solder Meniscus	↓	~const	↓
4. TEC Pellets Short Circuit	↓	↓	↓
5. Two-stage TEC: confused stage polarity.	~const	~const	↓**
6. TE material Degradation	↑	↓	~const

*- *~const @ low current*

**- *~ twice lower to nominal value*

At qualification and screening tests this approach allows retracing the history of the emerged defects and classify them.

It seems appropriate to take up more profound criteria of TEC rejection and their standardizing.

Acknowledgments

We are grateful to RMT technologists V.V. Volodin and D.E. Surov for great help in experimenting and testing.

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