Z-meter: Easy-to-use Application and Theory

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Abstracts

The paper is divided into two parts. The first part is an applying one. We present a handy, easy-to-operate user-addressing Z-meter. The device provides measurement of thermoelectric (TE) modules parameters: AC resistance (R), thermoelectric figure-of-merit (Z) and maximum temperature difference (ΔT_{max}).

The second part is of a theoretical value. As a rule, the device exposure does not happen to be ideally insulated and vacuum-like. Consequently need to take into consideration heat losses of various sorts. In this part we are to discuss specific formulae for estimating heat-exchanging uncertainties involved by Z-metering. All the expressions are explicit

On the basis of theoretical estimations it is advised and realized in Z-meter new availabilities to measure performance parameters of single stage TE modules with corrections factors, as well as modules mounted into packages and two-stage modules.

Introduction

Applications of thermoelectrical (TE) modules are becoming wider from year to year. Having started from commercial use mainly in consumer fields (TE refrigerators, cool boxes and so on) now applications of TE modules increase dramatically in optoelectronics, electronics laser technique and come from specialized fields, such as military and airspace, to commercial mass production.

In many emerging applications TE modules are critical components because they affect the temperature of the whole device, can have an effect on its correct operation, and impact on the heat dissipation.

That is why reliability requirements to TE modules are very high and are still growing even if comparing with consumer applications. That is why severe test procedures (precise and express) are required when a specific TEC type needs to be used in experimental and serial production.

Any TEC must provide high performance and a long operation lifetime without failure. The suggested failure criteria for reliability tests are the following:

- A drop in TEC maximum cooling capacity (Δ) below its specified rating. Measurements of Figure-of-Merit is used here as Δ
- An increase (5% is usual value) or higher in TEC resistance.

The reason of setting forward the two parameters is due to the AC Resistance ( ) and Figure-of-Merit (and, therefore, Δ calculated based on the value) being very sensitive to latent defects or damage of TE modules. The slightest change of these parameters during operation or storage could be the result of destruction of the TE module. That is why AC and are very useful for control of TE modules quality and reliability.

Although there are a lot of methods for measurement of TE modules parameters[1,2,3] only express methods are useful for certifications and mass production quality control.

On the basis of Harman method[4] our company RMT developed its own series of testing facilities (Z-meters) and has developed corresponding methods to examine a range of TE modules, as well as modules mounted into complete devices.

1. Classical Review of Harman Approach

Papers[4,5,6,7] describe and develop an approach for measuring thermoelectric (TE) properties and Figure-of-Merit of Peltier modules. This method was first suggested by T.C. Harman[4] in 1958 and bears his name.

A small current passes through the system generating a slight temperature differential along the module pellets. By measuring the Joule and Seebeck voltage drops one can find some thermoelectric parameters. Let us show it.

If the Peltier effect results in the temperature gradient $T_0<T_1$, in the simplest case the thermal rate equations for a 1-stage TEC can be written this way:

$$\begin{cases}\alpha I T_0 - \frac{1}{2} I^2 R - k\Delta T = \frac{a_0}{N}(T_a - T_0) \\ \alpha I T_1 + \frac{1}{2} I^2 R - k\Delta T = \frac{a_1}{N}(T_1 - T_a)\end{cases}, \qquad (1.1)$$

here - cold side temperature; - hot side temperature; Δ = ; - pellet thermal conductance; - pellet electrical resistance; - pellets number; - ambient temperature; - heat flux at the cold (=0) and hot (=1) sides. The energy dissipation should be small but enough for Joule losses runaway.

If the environment by the hot and cold sides are the same and in similar conditions, and in case cold and hot areas are equal, it is possible to admit

$$a_0 = a_1 = a \qquad (1.2)$$

Summing up two equations (1.1) and taking into account (1.2) we derive:

$$Z\overline{T} = \left(1 + \frac{a}{2Nk}\right)\frac{U_\alpha}{U_R}, \qquad (1.3)$$

where the Figure-of-Merit $Z=\alpha^2/kR=\alpha^2/\kappa\rho$ (α - Seebeck coefficient; κ and ρ - thermal conductivity and electrical resistivity respectfully), $\overline{T} = \frac{T_1 + T_0}{2}$ - the average sample temperature, $U_\alpha = \alpha\Delta T$, $U_R = IR$, I - the device current.

If (1.2) is justified and the current I is small enough, we can assume $T_0 = T_a - \xi$ and $T_1 = T_a + \xi$, and the average device temperature approximately equals the ambient temperature T_a.

With this assumption and in case ***a/2Nk<<1*** the main Harman relation takes the following form:

$$ZT_a = \frac{U_\alpha}{U_R} \qquad (1.4)$$

This relation is commonly used in thermoelectricity. However the $\overline{T} = T_a$ requirement remains not clear. We will discuss it further. Meantime, with the help of (1.1) and (1.4) ΔT_{max} is estimated as

$$\Delta T_{\max} = \frac{1}{2} ZT_0^2 \qquad (1.5)$$

Or, as related to the ambient temperature

$$\Delta T_{\max}(T_a) = T_a - \frac{\sqrt{1+2ZT_a} - 1}{Z} \qquad (1.6)$$

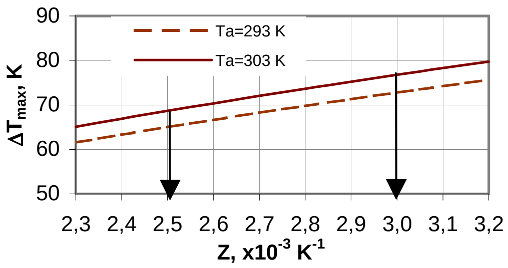

Fig. 1.2 The plot ΔT_{max} vs Z

In Fig. 1.2 the range of ***Z*** values (approx 2.5-3.0) commonly achieved by most of commercial TE modules suppliers is marked. That is why anyone can find that in standard specifications of the single stage TE modules ΔT_{max} falls within the range of 65-75 K.

2. Z-Meter Arrangement and Principles of Operation

The above described solution for the Z parameter requires accurate measurements of U_α, U_R and T_a. Additionally AC resistance is required for TE module qualification as mentioned above in

Z-meter Outside and Inside

For solution of the task we developed series of portable Z-Meters. The outlook of our Z-Meter is placed in Fig. 2.1.

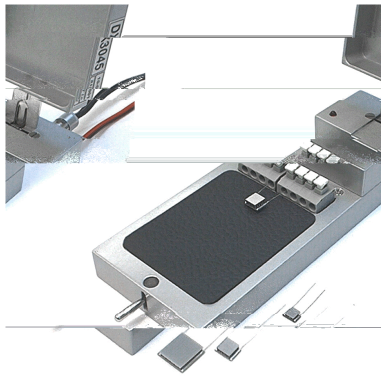

Fig. 2.1. The outlook of Z-Meter

The Z-Meter package is made of aluminium alloy. The metal package plays the role of passive thermostat for testing modules. Temperature o is measured with built-in digital thermometer with accuracy 0.1°C.

Measurement of AC resistance and Z parameters are performed separately. The ACR measurement is made first.

AC Resistance Measurement

Module is tested by AC current of small amplitude. The AC is simulated with the Commutator (Fig.2.3), which periodically (with 50% duty circle) reverses a circuit of a reference current .

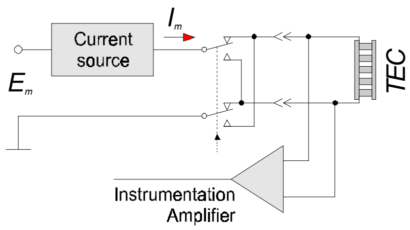

Fig. 2.3 Simplified Diagram of AC R Measurement

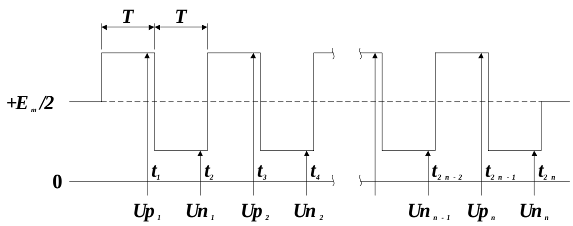

Fig. 2.4 Time diagram of AC measurement

In the no input signal state the output voltage of the Instrumentation Amplifier is equal to (Fig. 2.4).

During AC resistance measuring the output voltage is sampled and measured by 12 bit ADC every time before current reversing. The sampling points are marked as in the figure. The voltage drops and corresponding to the positive and negative polarities are used for a TE module resistance (R) calculation with the help of the following formula:

$$R = \frac{\sum_{i=1}^{n}(Up_i - Un_i)}{2 \cdot I_m \cdot A_V \cdot n} \qquad (2.1)$$

where - operating current; - voltage drop on TE module at positive operating current; - voltage drop negative

2. What is the current and, therefore, Joule heating limitation?
3. If the TEC is not in vacuum, what way is ratio (1.4) modified and what corrections are to be calculated?
4. What way is ratio (1.4) transformed and what are the means of allowing for asymmetry, that is for a real case when (1.2) is not true?

Commonly the thermal rate equations for a 1-stage TEC must be written the following way:

$$\begin{cases} \alpha I T_0 - \frac{1}{2} I^2 R - k' \Delta T = a_1 (T_a - T_0)/N \\ \alpha I T_1 + \frac{1}{2} I^2 R - k' \Delta T = a_2 (T_1 - T_a)/N \end{cases}, \tag{3.1}$$

where N is pellets number, a - thermal conductance from the outer cold side, is thermal conductance from the outer hot side ($a_1 \neq a_2$), $'$ is effective pellets thermal conductance allowing for the air and electromagnetic field between them.

The term describes thermal conductance normalized to one pellet between the cold and hot surfaces:

$$k' = k(1 + b_{th}) , \tag{3.2}$$

where

$$b_{th} = B_{cond} + B_{rad} , \tag{3.3}$$

The B_{cond} and B_{rad} are corrections for inter-pellet thermal conductance values through air thermal conductivity and radiation, respectively:

$$B_{cond} = \frac{\kappa_{air}}{\kappa}\left(\frac{1}{\beta} - 1\right) , \tag{3.4}$$

Here pellets filling term is:

$$\beta = \frac{Ns}{S} , \tag{3.5}$$

where S is cold side dimensions;

$$B_{rad} = \gamma \frac{S}{Nk} \sigma T_a^3 (1 - \beta) , \tag{3.6}$$

where σ - Boltzman constant, γ - thermal emissivity.

As for (3.6) it can only be regarded as a rough estimate. We do not take into account air convection between the pellets as Grasgof and Prandtl criteria show for this case[8]

Solving equations (3.1) we find the following:

$$T_1 = \frac{1}{\left(\frac{\alpha^+ \alpha^-}{(k')^2} - 1\right)} \left(\frac{\alpha^+ \left(\frac{1}{2} I^2 R + \frac{a_2}{N} T_a\right)}{(k')^2} + \frac{\left(\frac{1}{2} I^2 R + \frac{a_1}{N} T_a\right)}{k'} \right) , \tag{3.7}$$

$$T_0 = \frac{1}{\left(\frac{\alpha^+ \alpha^-}{(k')^2} - 1\right)} \left(\frac{\alpha^- \left(\frac{1}{2} I^2 R + \frac{a_1}{N} T_a\right)}{(k')^2} + \frac{\left(\frac{1}{2} I^2 R + \frac{a_2}{N} T_a\right)}{k'} \right) \tag{3.8}$$

,

where

$$\alpha^+ = k' + \frac{a_1}{N} + \alpha I \text{ and } \alpha^- = k' + \frac{a_2}{N} - \alpha I \tag{3.9}$$

Transforming equations (3.8) with

$$\frac{a_1}{N} << k', \ \frac{a_2}{N} << k' \text{ and } I << \frac{k'}{\alpha} , \tag{3.10}$$

we have

$$\bar{T} = T_a \left(1 + \frac{a_1 a_2}{N(a_1 + a_2)k'}\right) + \frac{I^2 RN}{a_1 + a_2}\left(1 + \frac{a_1 + a_2}{4nk'}\right) + T_a \frac{\alpha I (a_2 - a_1)}{2k'(a_1 + a_2)} \tag{3.11}$$

and

$$\Delta T = \frac{\alpha I}{k'}\left(T_a + \frac{I^2 RN}{a_1 + a_2}\right) + \frac{a_1 - a_2}{k'(a_1 + a_2)} \frac{I^2 R}{2} \tag{3.12}$$

Let us discuss in what way Harman Z-measuring involves the above mentioned.

Allowing for (3.12) we obtain the following expressions for the thermoelectric power and voltage ratio:

$$U_\alpha = \frac{\alpha^2 IN}{k'}\left(T_a + \frac{I^2 RN}{a_1 + a_2}\right) + \frac{(a_1 - a_2) I^2 RN\alpha}{2k'(a_1 + a_2)} \tag{3.13}$$

$$\frac{U_\alpha}{U_R} = \frac{\alpha^2}{k'R}\left(T_a + \frac{I^2 RN}{a_1 + a_2}\right) + \frac{(a_1 - a_2) I\alpha}{2k'(a_1 + a_2)} , \tag{3.14}$$

or

$$\frac{U_\alpha}{U_R} = Z'\left(T_a + \frac{I^2 RN}{a_1 + a_2}\right) + \frac{(a_1 - a_2) I\alpha}{2k'(a_1 + a_2)} , \tag{3.15}$$

where $Z' = \frac{\alpha^2}{k'R}$. Unlike equations (1.2) – (1.4) relation (3.14) contains directly the ambient temperature. If using the average temperature (see (1.3) and (3.11)) we should have allowed for the additional term ~ $a/2Nk$ characterizing heat dissipation from the external surfaces. Formula (3.14) takes this term into account automatically via T_a, leaving just the corrections discussed below.

So, the true Z $(=\alpha^2/kR)$ could be defined as

$$Z = \frac{1}{T_a(1 + b_T)}\left\{\frac{U_\alpha}{U_R}(1 + b_{th})(1 + b_r) + b_A\right\} , \tag{3.16}$$

where

1) $b_T = \frac{1}{T_a}\frac{I^2 RN}{a_1 + a_2}$ - Correction factor to ambient temperature

2) $b_A = \frac{(a_2 - a_1) I\alpha}{(a_2 + a_1) 2k}$ - Correction factor because of asymmetry of heat exchange with environment;

3) $b_{th} = B_{cond} + B_{rad}$ - Correction factor to pellet thermoconductivity due to additional heat flux from warm to cold side through the ambient (according to (3.3));

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4) $b_r = \dfrac{r}{R_{TEC}}$ - Correction factor because of non-zero resistance of TE module wires where $R_{TEC} = NR$ (The total voltage drop is a sum of the drop at the module and some additional drop at contacting wires (

- surface and length of the heat sink , correspondingly.

In Fig.4.2-4.3 we demonstrate the effect of heat sink on the effective Figure-of-Merit measured by the technique on the basis of equation 3.16 and 4.1.

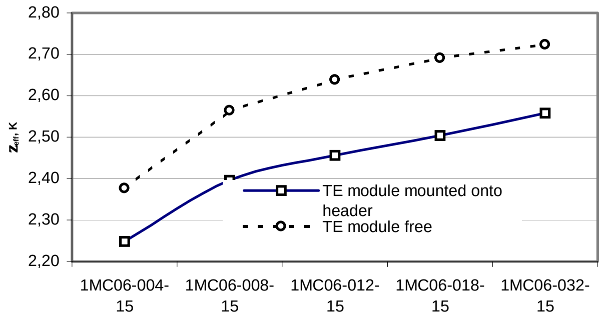

Fig. 4.2 Effective of TE modules free and mounted one onto heat sink module (Z=2.8x10^{-3} K)

One can see that mounting of a TE module onto the heat sink leads to decrease of the measured in comparison with the effective of the TE module in the free space. In Fig. 4.4 we demonstrate experimental results of measurement of TE modules before and after mounting. The results are in good correlation with the above theoretical estimations.

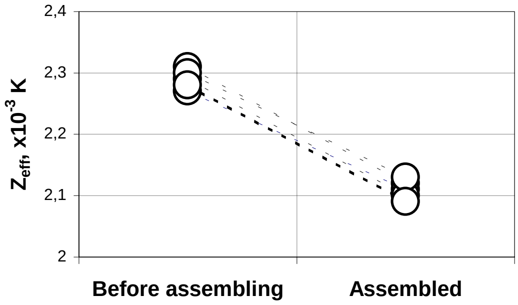

Fig. 3.4 Effective Z_{eff} measured before and after assembling of TE modules (1MT03-012-15) onto TO5 headers

The positive result of the above estimations is that the measured for assembly correlates with the true performance of a TE module.

Of course, assumptions made in theoretical approach put many limitations in application of Z-metering technique for specific packages and arrangements of mounted TE modules.

Nevertheless there are two ways to use the technique for examination of assembled TE modules:

1. One can analyze equations 3.15 and 3.16 and find that averaging of measuring results of two cases with change of the current polarity allows to exclude effect of the heat sink on resulted.

The second term in 3.14 and 3.16 generates a certain correction. It is remarkable however that this term is a linear function of the current. Then marking one of polarities by (+), and the other by (-) we have:

$$\left(\frac{U_\alpha}{U_R}\right)_+ = \frac{\alpha^2}{k'R}\left(T_a + \frac{I^2RN}{a_1+a_2}\right) + \frac{(a_1-a_2)I\alpha}{2k'(a_1+a_2)} \qquad (4.2)$$

$$\left(\frac{U_\alpha}{U_R}\right)_- = \frac{\alpha^2}{k'R}\left(T_a + \frac{I^2RN}{a_1+a_2}\right) + \frac{(a_2-a_1)I\alpha}{2k'(a_1+a_2)} \qquad (4.3)$$

Summing (4.2) and (4.3) we come to:

$$\left(\frac{U_\alpha}{U_R}\right)_+ + \left(\frac{U_\alpha}{U_R}\right)_- = 2Z'\left(T_a + \frac{I^2RN}{a_1+a_2}\right)_a \qquad (4.4)$$

that is we manage to solve the problem avoiding any corrections challenge.

2. It is possible to introduce some empirical correction factor that is certainly unique for a concrete package and arrangement of assembly, like as TO standard types, for instance, or others.

3. The effective parameter Z_{eff} directly measured without any corrections can be used as a failure criterion for reliability tests of assemblies.

5. Z-measuring of a 2-stage TEC

If placing a two-stage TE module into the Z-Meter it is possible to measure some value $\frac{U_\alpha}{U_R}$ as could be done for a single stage module.

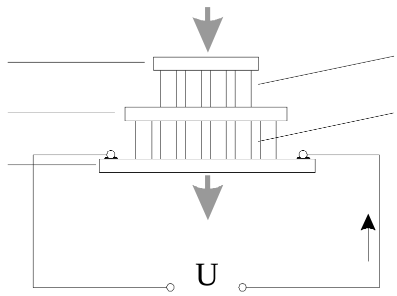

Fig. 5.1. A view of a 2-stage TEC

Let us consider if this ratio correlates with the true value of a two-stage module and whether it is possible to transform the correlation into a similar Harman equation. In other words: is it possible to apply the Harman method to two-stage TE modules?

A simplified drawing of two-stage TE module is placed at Fig. 5.1.

The general formulae for a two-stage module cold and hot sides are:

$$\begin{cases} \alpha I T_0 - \frac{1}{2}I^2R - k'_1(T_1 - T_0) = \frac{a_0}{N_1}(T_a - T_0) \\ \alpha I T_2 + \frac{1}{2}I^2R - k'_2(T_2 - T_1) = \frac{a_1}{N_2}(T_2 - T_a) \end{cases}, \qquad (5.1)$$

where T_0, T_1 and T_2 - TE module's cold side, medium and hot side temperatures, respectively.

Since $a_i = A_i S_i$ and assuming the stage pellets number $N_i \sim S_i$ where is the cold side area of the corresponding stage, we can make approximations

$$\frac{a_1}{N_1} = \frac{a_2}{N_2} = A = const \tag{5.2}$$

$$\beta_i = \frac{N_i s}{S_i} = const \tag{5.3}$$

Taking (5.2) and (5.3) and setting $k'_1 = k'_2 = k'$ we modify (5.1) the following way:

$$\begin{cases} \alpha I T_0 - \frac{1}{2} I^2 R - k'(T_1 - T_0) = A(T_a - T_0) \\ \alpha I T_2 + \frac{1}{2} I^2 R - k'(T_2 - T_1) = A(T_2 - T_a) \end{cases} \tag{5.4}$$

Summing up equations in (5) we derive:

$$2\alpha I \overline{T} = (k' + A)\Delta T \ , \tag{5.5}$$

where $\overline{T} = \frac{T_2 + T_0}{2}$ is the average module temperature.

Solving the following set of equations

$$\begin{cases} 2\alpha I \overline{T} = (k' + A)\Delta T \\ I = \frac{1}{2R}\left(\frac{U_{R_1}}{N_1} + \frac{U_{R_2}}{N_2}\right), \\ \Delta T = \frac{1}{\alpha}\left(\frac{U_{\alpha_1}}{N_1} + \frac{U_{\alpha_2}}{N_2}\right) \end{cases} \tag{5.6}$$

we obtain the following

$$Z\overline{T} = (1 + b_{th})(1 + b_r)\frac{U_\alpha}{U_R} \ . \tag{5.7}$$

Here

$$b_{th} = B_{cond} + (B_{conv} + A_{conv}) + (B_{rad} + A_{rad}) \tag{5.8}$$

The parameters $B_{cond}, B_{conv}, B_{rad}$ are described above (3.4-3.7).

$$A_{conv} = \frac{al}{\kappa\beta} \tag{5.9}$$

$$A_{rad} = \frac{\gamma}{\kappa\beta}\sigma T_a^3 l \tag{5.10}$$

Equation (5.7) is rather similar to (1.4) and (3.18). It proves that we can apply the Harman method to a 2-stage TEC meeting requirements (5.2) and (5.3).

Of course, the equation for estimation of Δ for single stage modules (1.5) is not valid here. But knowing the   value we can evaluate Δ finding the maximum of the following function:

$$\Delta T(x) = T_a - \frac{x^2}{2Z(x+1)} - \frac{1}{((\xi - 1)x + \xi + 1))(x+1) - 1} \times \left[(\xi + 1)\frac{x^2}{2Z} + T_a + \frac{x^2}{2Z(x+1)}\right]$$

Thus the Harman method could be used for estimation of two-stage TE modules.

In Fig. 5.2-5.4 we demonstrated calculated results and taking into account above advised corrections to estimate value of two stage modules basing on the data measured by the Z-meter.

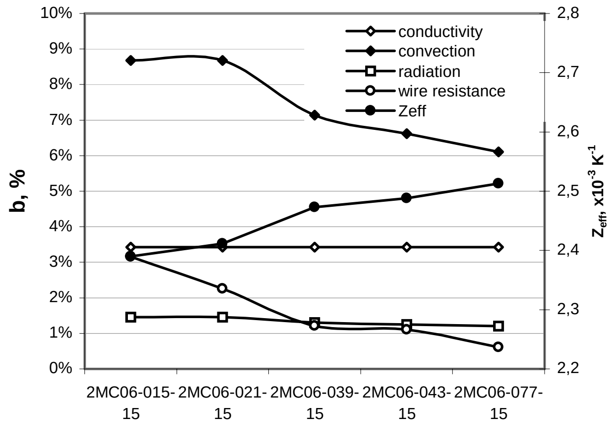

Fig. 5.2 Correction factors for 2MC06-   -15 TEC types

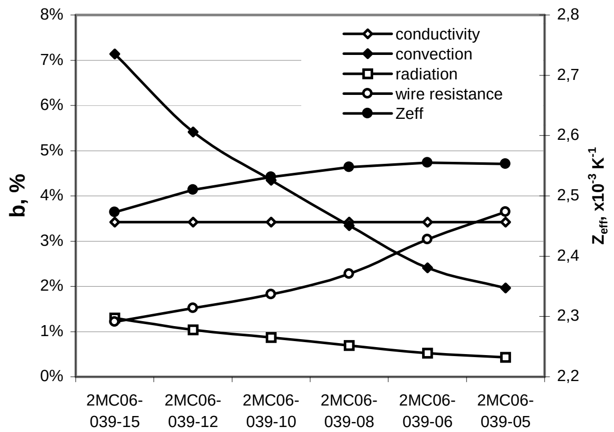

Fig. 5.3 Correction factors for 2MC10-039-   TEC types

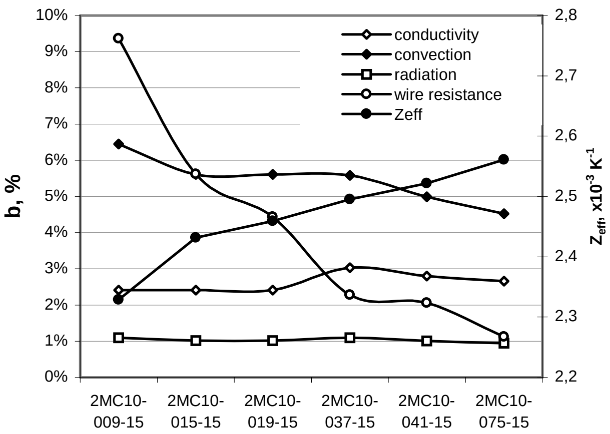

Fig. 5.4 Correction factors for two stage TEC types of 2MC10

i f t4.4 1(4.4 M)4.71(e2.23(a.451(urem)2(ent 0 0 11.04 288.74 11 TT0 4176.8(C)6(107(i)-1684 1 9.36t)4.l1(h)m0.)4.l1(A)