Quality Testing of Two-Stage Thermoelectric Cascades

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Abstract

The usual practice of quality testing manufactured two-stage thermoelectric modules (TSTM's) is to measure their maximum temperature differential in a high-vacuum system using a temperature-controlled, constant base plate. This is very difficult, time-consuming, expensive and requires sophisticated, complex equipment. As such, it is not practical to assure quality of TSTM's on a 100% basis. Therefore, it is desirable to create a new test method for these TE coolers which shortens test time and minimizes experimental error.

This paper describes the development of a new testing method for TSTM's which takes advantage of the transient method developed by Buist [1] and/or the modified Harman [2] method developed by Gorodetskiy [3]. This method basically consists of electrically isolating the bottom and top stages and testing the characteristics of the bottom and top stages individually by auxiliary wires, if needed.

The accuracy and validity of this test method was developed by pre-characterizing each stage (prior to TSTM assembly) as individual TE modules via methods [1] and [3]. After TSTM assembly, the proposed new test method was applied and compared with component test results. Although the implied "modular" approach to TSTM fabrication was applied to validate results, this new test method applies to all TSTM's if auxiliary wires are either not needed or attachable.

Introduction

If a TM has two stages connected in series and if top stage current terminals are accessible or, at least, two auxiliary wires can be attached thereto, it is possible to test the top and the bottom stages in separate measurements. To measure the top stage parameters the computer-aided test system has to be connected to these inter-stage test points (or auxiliary wires). When the computer-aided system is connected to a TSTM input terminals and the inter-stage test points are short-circuited, the bottom stage parameters can be measured.

It has been previously shown by Lau [4] that although the time constant of a TE module is doubled by being "heat sunk" (compared to a suspended module), the measured figure of merit, Z, of a typical TE module via the Transient Method [1] agreed within 0.8%. Therefore, for practical purposes, it was inferred through these tests that the correction factors due to the dormant, passive stage would be quite small in most cases. This observation was the key to accurately testing the individual stages of a TSTM using either method [1] or [3]. That is, it would be only necessary to isolate the test current to either stage, top or bottom. These two separate tests could then be used to ascertain the overall quality of the TSTM.

Correction Factor Analysis

The resistance of the auxiliary wires must be considered in the measurement of the figure of merit, Z, and resistance, R, of the top and bottom stages. In order to have negligible corrections for resistance of the wires, their length/area must be small enough to have negligible resistance compared with the resistance of each stage. Therefore, if auxiliary wires are needed, they should be only long enough for connecting with Kelvin clips.

In both test procedures, test current does not flow through one of the stages. The additional heat exchange of this dormant stage with environment has to be taken into account, when the corrections to measurement results are made. The corrections to Harman expression can be made as in [3], where the calculations were performed by thermoelectric module (TM) energy balance analysis in steady state conditions. When a test current flows through the stage under test, the Joule heating, thermal conductance of air, heat flow through wires, and heat exchange with environment by radiation and convection were taken into account using an energy balance analysis. For this purpose, a simultaneous solution of the following two heat exchanger heat balance equations must be obtained:

$$- Sm*I*Tc + I^2*R/2 + (K+Ka)*\Delta T + Hv*(Ta-Tc) = 0 \qquad (1)$$

$$Sm*I*Th + I^2*R/2 - (K+Ka)*\Delta T - Hn*(Th-Ta) = 0 \qquad (2)$$

Equations (1) and (2) are related to cold and hot heat exchangers, respectively. The symbols used in the equations are defined as follows:

Sm is the Seebeck coefficient of the stage under test defined by: $Sm = N* (|Sn|+|Sp|)$ where $|Sn|$ and $|Sp|$ are the absolute values of n-type and p-type element Seebeck coefficients, respectively. N denotes the number of thermocouples in the stage under test. R and K are stage resistance and thermal conductance, respectively. Ka designates the thermal conductance of air, sandwiched between stage ceramics. I is the test current. $\Delta T = Th - Tc$. Tc, Th and Ta are the temperatures of cold and hot heat exchangers and of the environment, respectively. Hv and Hn are effective heat conductances of heat exchange processes between a corresponding exchanger and environment.

Effective heat exchange coefficients due to convective and radiative processes between the heat exchange coefficient due to heat contact between the plate and lead wires is also included in Hn as the sum, or effective overall coefficient of all of these effects. It is considered, that lead wires have heat exchange with environment due to convective and radiative processes and current wires Joule heating could be neglected. If the current were reversed, one would have to interchange the position of Hv and Hn in (1) and (2). When the top stage of the TSTM is under test, its Hv will be the same as for a usual thermoelectric module. However, Hn includes an additional heat exchange owing to the passive bottom stage. When the bottom stage of the TSTM is under test, Hn will be the same as for a usual thermoelectric module and Hv will include an additional heat exchange owing to the passive top stage.

Hv and Hn can be estimated by methods described by Dulnev [5], if all heat exchanger dimensions and distances between its outer surface and thermostat inner walls are known. Let us denote temperature difference Th - Ta by ΔTh, Ui = I*R + Us and Us = Sm*ΔT; and point out, that the difference Ta - Tc is equal to ΔT - ΔTh. Subtracting (1) from (2) one can obtain:

$$Z= \frac{Us}{Ta(Ui-Us)} * \frac{Ta}{Ta+\Delta Th-\Delta T/2} * (1+ \frac{Hv(\Delta T-\Delta Th)+Hn\Delta Th}{(2*(K + Ka)\Delta T)} \quad (3)$$

Where denoted by Z a TM figure of merit in air is equal to:

$$Z = Sm^2/(R*(K+Ka)) \quad (4)$$

The equation (3) differs from the Harman expression by two correction factors that, by first approximation, may be taken as 1. The first of them is a ratio of environment temperature Ta to stage under test mean temperature, that is equal to Ta+ΔTh-ΔT/2. The second one takes properly into account the influence of heat exchange between the stage under test and environment on stage figure of merit. A following equation can be obtained from the sum of (1) and (2):

$$\Delta Th = (Hv*\Delta T + I*Ui) / (Hv+Hn) \quad (5)$$

A stage resistance, R, that was measured at mean TM temperature, is to be related to a temperature of 295K by temperature coefficient of TM resistance that is equal to 0.45 percent/K :

$$R = ((Ui-Us)/I)*(1+0.0045*(295-Ta-\Delta Th+\Delta T/2)) \quad (6)$$

By the first approximation, the values ΔT and ΔTh in (6) may be taken as zero.

By successive approximation, the Seebeck coefficient Sm can be calculated from expression (4) if the heat conductivity of TM elements and air, and dimensions of all TM parts are known.:

$$Sm = (Z*R*(K + Ka))^{1/2} \quad (7)$$

Thus, the temperature difference ΔT can be calculated from:

$$\Delta T = Us/Sm \quad (8)$$

By successive approximation, the ΔTh, Z and R values can be calculated from expressions (5), (4) and (6), respectively. The iterative scheme converges to unique solution rapidly for a TSTM stage.

All numerical calculations were performed for a TM suspended on wires by Kelvin clips and located in a space of the passive thermostat. The resistance of the auxiliary wires was taken equal to zero. Calculations were performed on a TSTM fabricated from a TM, model TB-83-1.0-1.3 as the bottom stage and a TM, model TB-31-1.0-1.3 as the top stage. These results indicated that the as-measured, non-corrected Z was reduced by approximately 0.7 percent and 2.3 percent for the bottom stage and top stage, respectively

It was also determined that the vacuum value of the TM figure of merit can be obtained, if the corrected value of Z is multiplied by a factor (1+Ka/K).

Experimental

A set of thermoelectric modules were designed and manufactured by Cryotherm, St. Petersburg, Russia especially for experimentally verifying the TSTM test procedures described in this paper. The module designated for the top stage was a 31 couple module with TE pellets 1.0 x 1.0mm in cross-section and 1.3mm tall (model TB-31-1.0-1.3). The only difference between this TE module and "regular" TE modules was that both substrate surfaces were metallized and pre-tinned with low temperature solder for joining to the bottom stage.

The TE module designated for the bottom stage was a 83 couple module with TE pellets identical to the top stage. This module was designated: model TB-83-1.0-1.3. This "bottom stage" was also metallized on both substrate surfaces, but also had some other unique features. One of its cold side conducting tabs, which would normally connect the cold sides of the adjoining TE pellets, was replaced with two separate conducting tabs which faced outward. This modification, therefore, created an open circuit.

Of course, these "output tabs" could be easily electrically shorted to complete the normal TE module electrical network and, thus, provide the means for testing it as a "normal" TE module. Indeed, this was done in order to test it, and the top stage separately as "normal" TE modules for their thermoelectric parameters. This "Before" test data is given in Tables 1 and 2 for two sets of bottom and top stages, serial numbers #1 and #2 for each pair of stages.

The TSTM fabrication process was to solder the smaller TE module onto the cold side of the larger TE module, thereby forming the structure of a TSTM. The final step in this procedure was to connect wire "jumpers" from the un-shorted output tabs of the bottom stage to the electrical input tabs of the smaller, top stage. The resultant was the formation of two each 2-stage thermoelectric modules, TSTM#1 and TSTM#2, on which subsequent testing was performed in normal, room-temperature, still air.

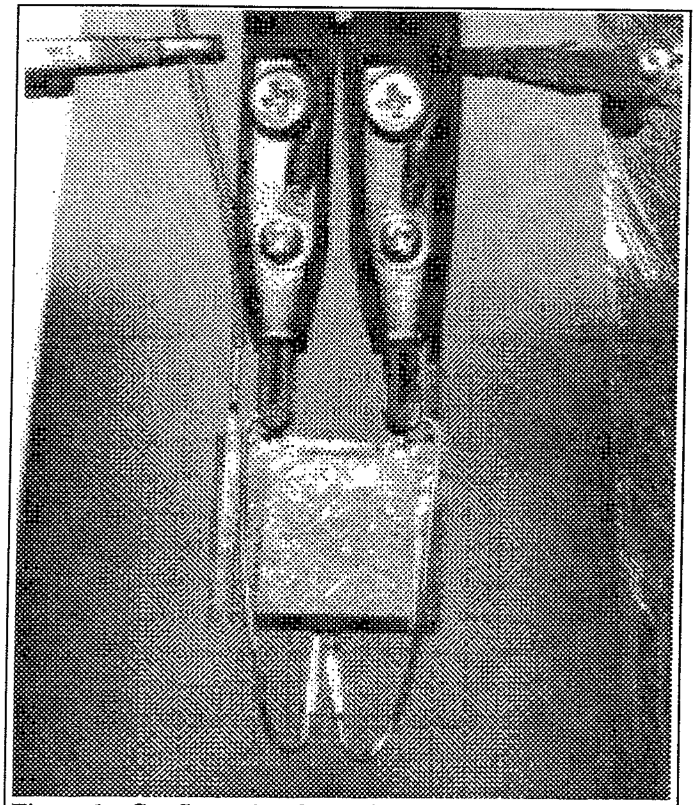

Figure 1. Configuration for testing the top stage in air.

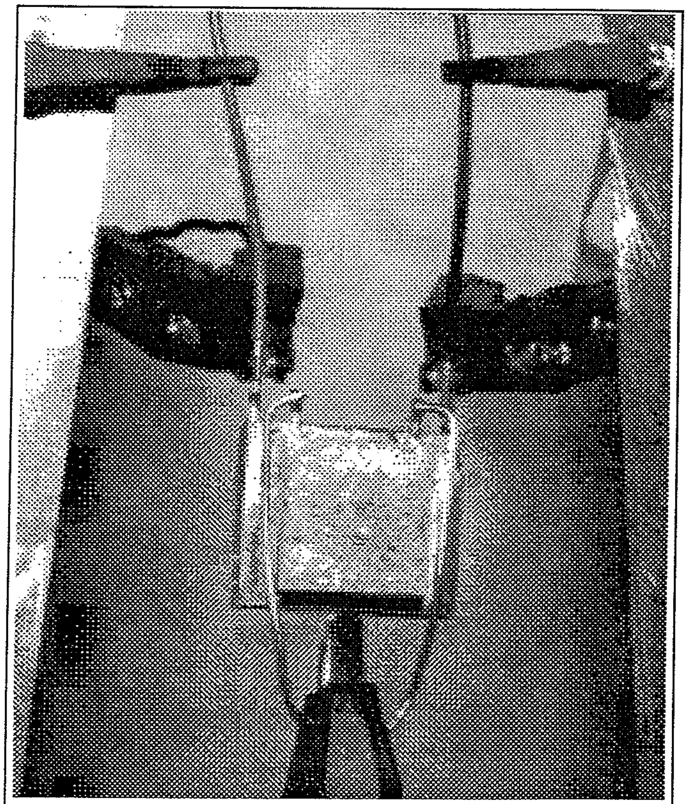

Figure 2. Configuration for testing the bottom stage in air.

Testing the Top Stage of the TSTM's

To test the top stage of the 2-stage cascades, it was very important to suspend the TSTM such as that shown in Figure 1, where extra clips are fastened to the insulated input leads of the TSTM. Significant errors were observed when the TSTM was attached to a heat sink. This was because the passive stage already acted as a heat sink and an additional heat sink significantly thermally loaded the stage under test and reduced the measured Z. Finally, "Kelvin" clip test probes were clipped to each of the "jumpers" to the top stage as illustrated in Figure 1, leaving the electrical input leads of the bottom stage totally isolated. For some manufactured TSTM's it may have been necessary to attach auxiliary test probes at these points as described above. However, for this case it was quite easy to simply clip to the jumper wires at their point of connection to the top stage. All that was needed was to test the top stage just as if it were a separate, independent TE module. During the test, the test current passed only through the top stage. The dormant bottom stage acted as a heat sink, as mentioned before. Certainly, the bottom stage slightly heated during one test current polarity and slightly cooled during the other test current polarity. However, as described in the introduction and analysis given above, this was only a minor perturbation from the fully isolated tests on this same stage performed before cascade assembly. The data from this test of the assembled TSTM's #1 and #2 are given in Tables 1 and 2, designated "After".

Testing the Bottom Stage of the TSTM's

This test configuration required that the top stage be electrically shorted to eliminate any test current from entering the top stage. This was accomplished by clipping an extra clip lead to the two jumper wires, shorting them together as shown in the lower portion of Figure 2. Whenever auxiliary wires are needed, this same condition can be accomplished by simply shorting these wires together. After this top stage shorting was secured, test Kelvin clips were applied to the bottom stage input wires as shown in the upper portion of Figure 2. Testing was subsequently performed on the bottom stages of both TSTM's. The test data gathered is given in Tables 1 and 2, designated "After". It is clear that good agreement exists between the "Before" and "After" data sets, proving the effectiveness and dependability of this procedure to quickly and accurately ascertain TSTM quality.

Table 1.
Tested Resistance and uncorrected Z of TSTM#1 stages

	Top Stage		Bottom Stage	
	Resistance (Ohm)	Z*1000 (/K)	Resistance (Ohm)	Z*1000 (/K)
Before	0.775	2.394	2.227	2.574
After	0.808	2.415	2.294	2.553
Diff.	4.25%	0.88%	3.01%	-0.82%

Table 2.
Tested Resistance and uncorrected Z of TSTM#2 stages

	Top Stage		Bottom Stage	
	Resistance (Ohm)	Z*1000 (/K)	Resistance (Ohm)	Z*1000 (/K)
Before	0.794	2.440	2.288	2.602
After	0.806	2.465	2.339	2.550
Diff.	1.51%	1.02%	2.23%	-2.00%

Conclusions

The testing required to assure the quality of a 2-stage cascade by conventional cooling performance test methods can be a long and laborious problem. Therefore, it is not practical to test the TE cooling modules at a very high acceptance quality level (AQL). However, a method has been presented in this paper which reduces test time to such a degree that 100% testing of 2-stage thermoelectric cascades is now economically practical and effective.

Obviously, the key to this test method is to have a computer-aided test system that is capable of quickly and accurately obtaining data such as that described in [1] or [3]. It is then only necessary to suspend the 2-stage cascade (in open air) and configure the test probes equivalent to that shown in Figures 1 and 2. The actual test procedure is then as simple and quick as testing individual single-stage TE modules, taking only a minute or two for the bipolar testing of each stage. The data gathered can not only be used to ascertain and validate the quality of the cascade, it also provides the TE material property data which can be used in an effective TE modeling program [6] to determine the cooling performance of the cascade at literally any thermal and electrical condition.

Acknowledgments

The authors would like to acknowledge the contributions of Todd M. Ritzer and Julie A. Witkop of TE Technology, Inc., USA for assembling and instrumenting the two-stage cascades fabricated from individual single-stage TE modules provided by Cryotherm, St. Petersburg, Russia. The authors would also like to acknowledge the support and contributions to the hardware and the assistance provided in the preparation of the manuscript by V.E. Baukin and S.V. Zarubo of Cryotherm, St. Petersburg, Russia.

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