Convection Correction Factor Determination for Use with the Transient Test Method for Thermoelectric Modules

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Abstract

The transient test method used by TE Technology, Inc. requires a small temperature difference to be developed across a thermoelectric module to measure its figure-of-merit, Z. Correction factors associated with radiation, conduction, and convection must then be applied to the measurements to determine the actual Z of the N and P average of the thermoelectric materials comprising the module. The accuracy of these correction factors will affect the accuracy of the Z. Radiation and conduction can be calculated with the same accuracy regardless of the size of the module, but convection is inherently size dependent. Factoring in the temperature dependence for convection is also more complex. Therefore, several different sizes of modules were measured in air and in vacuum. Comparison between the Z measured in vacuum and in air was used to test the validity of convection correlations as applied to thermoelectric modules. Recommendations are made for the best correlation to use in determining the convection correction factor.

Introduction

There are several ways to test a thermoelectric module, but regardless of the type of test, it is done in air (or some inert gas) or in a vacuum. Testing in air is much easier and faster. These two test characteristics, fast and easy, are of primary importance in a manufacturing environment where cost must be tightly controlled and superior quality must be maintained.

The "Transient Test Method" (TTM) [1] requires that a small amount of current be applied to the module to test it. Consequently, correction factors must be applied to the measured figure-of-merit (Z) in order to account for the heat loads from radiation, conduction, and convection incurred from applying the test current. None of these heat loads is easy to calculate because of the three-dimensional, relatively complex geometry in typical modules. However, both radiation and conduction are not inherently geometry dependent to the extent that natural convection is.

Testing in a vacuum removes any difficulties associated with testing a module in air. The thermoelectric properties that are measured are more certain since only radiation effects must be considered. Unfortunately, testing in a vacuum requires a considerable amount of setup time, so it would not be particularly suited for implementing quality control in large volume productions.

Available heat transfer correlations were evaluated for their ability to serve as convection correction factors as used in the TTM. Recommendations are made for the best heat transfer correlation to use when testing in an ambient air environment so that testing in air would be accurate as well as being fast and easy. In addition, the effect of vacuum pressure level on measurements was also considered.

Test setup and procedure

Tests in air and in vacuum were performed using TE Technology, Inc.'s TS-001DS which utilizes the TTM to measure thermoelectric properties accurately. There were two module configurations for testing: 1) suspended, in the thermocouple mode and 2) module lying on its side, no-thermocouple mode.

In configuration 1, the figure-of-merit multiplied by the temperature (ZT), the AC-resistance (ACR), the Seebeck coefficient, and the actual temperature of the module were all directly measured. All tests using configuration 1 were tested in a vacuum. Figure 1 shows the vacuum test stand.

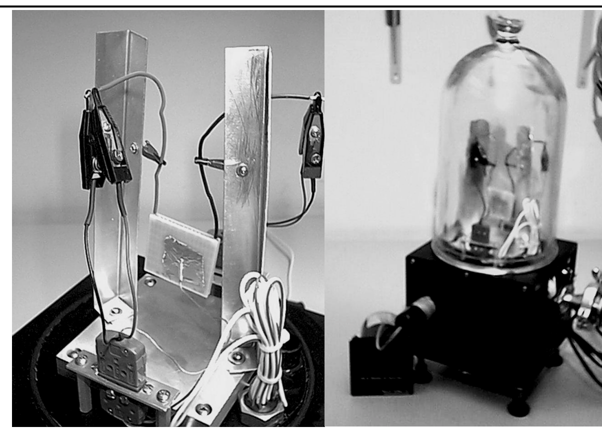

Figure 1. Vacuum Test Setup

In configuration 2, only one thermocouple was used to measure the average temperature of the module under test. This average temperature basically corresponded to the ambient temperature. The ZT, the average module temperature, and the (ACR) of the module were directly measured. All other parameters were calculated. All tests using configuration 2 were tested in air. Figure 2 shows the in-air test setup.

Several different sizes (different number of couples) and types (different Imax) of modules were tested. Module geometry and nominal performance specifications are shown in Tables 1 and 2. The geometry given in Table 1 is for the overall dimensions for each module.

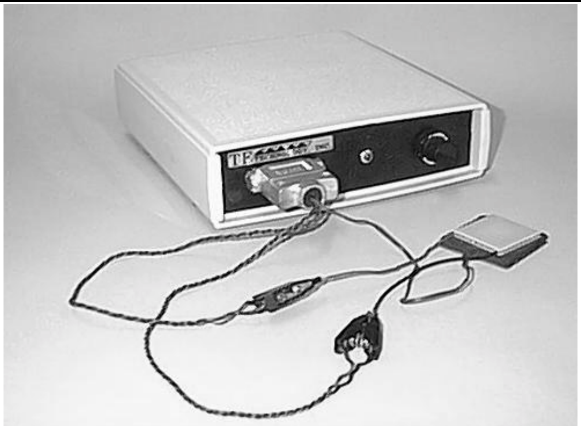

Figure 2. In-air Test Setup

Table 1. TE Module Geometry

Module Number	Width 1 (mm)	Width 2 (mm)	Height (mm)
1	47.9	47.8	3.72
2	49.9	49.9	5.40
3	39.9	39.8	3.98
4	40.0	40.0	3.82
5	21.0	39.9	4.12
6	7.34	7.36	3.46
7	40.0	40.0	3.90

Table 2. Nominal TE Module Performance Specifications

Module Number	Imax (A)	Vmax (V)	Qmax (W)	ΔTmax (°C)
1	9.3	15.2	78.0	67
2	7.6	15.4	77.0	67
3	6.0	15.4	51.4	67
4	8.2	15.2	69.0	67
5	8.5	7.6	34.1	65
6	6.0	8.6	28.7	65
7	6.2	16.5	64.0	73

The test current that was applied in each case was that as calculated by the TTM. This current was determined on the assumption of testing typical Bi-Te based thermoelectric modules such that approximately a 4°C to 6°C temperature difference would be developed.

Each module was first tested using configuration 1. Next, a natural convection heat transfer coefficient was then calculated based on module geometry and ambient temperature. Then each module was tested using configuration 2 using the appropriate convection correction factor for that particular module. Temperature dependent corrections were then applied to represent all values at 25°C by using algorithms derived from the characteristic behavior of Bi-Te based modules [2]. The actual temperatures at which the modules were tested differed from 25°C by at most 5°C; therefore, any errors incurred by these temperature corrections would be minimal.

Heat transfer correlations

Some heat transfer correlations for natural convection may not generally apply to situations of testing modules with the TTM. This is because the temperature difference between the module and the ambient amounts to only a few degrees Celsius thereby creating only a small buoyancy driving force for natural convection. Correlations readily available in the general literature have only been verified when larger driving forces are present. In some cases, too, convection might be a mix of natural and forced in a general manufacturing environment where modules might be tested for quality control. Nonetheless, these natural convection correlations were evaluated for their potential applicability to testing modules.

Several natural convection correlations are presented below for horizontal surfaces: [3], [4], [5]

$$\overline{Nu_L} = 0.54\,Ra_L^{1/4} \tag{1}$$

$$\overline{Nu_L} = 0.657\,Gr_L^{1/5}\,Pr^{1/4} \tag{2}$$

$$Nu^T = \frac{0.560285}{\left[1+\left(0.492/Pr\right)^{9/16}\right]^{4/9}}\,Ra_L^{1/4} \tag{3a}$$

$$Nu_l = \frac{1.4}{\ln(1+1.4/Nu^T)} \tag{3b}$$

$$Nu_t = 0.14\left(\frac{1+0.0107\,Pr}{1+0.01\,Pr}\right)Ra_L^{1/3} \tag{3c}$$

$$\overline{Nu_L} = \left[Nu_l^{10} + Nu_t^{10}\right]^{1/10} \tag{3d}$$

Likewise, below are some correlations for heat transfer from a vertical surface: [4], [6], [5]

$$\overline{Nu_L} = 0.68 + \frac{.67\,Ra_L^{1/4}}{\left[1+\left(0.492/Pr\right)^{9/16}\right]^{4/9}} \tag{4}$$

$$\overline{Nu_L} = 0.68\,Pr^{1/2}\,\frac{Gr_L^{1/4}}{\left(0.952+Pr\right)^{1/4}} \tag{5}$$

$$Nu^T = \frac{0.671\,Ra_L^{1/4}}{\left[1+\left(0.492/Pr\right)^{9/16}\right]^{4/9}} \tag{6a}$$

$$Nu_l = \frac{2}{\ln\left(1+2/Nu^T\right)} \tag{6b}$$

$$Nu_t = \frac{C_t Ra_L^{1/3}}{1+1.4x10^9\,Pr/Ra_L} \tag{6c}$$

$$C_t = \frac{0.13\,Pr^{0.22}}{\left(1+0.61\,Pr^{0.81}\right)^{0.42}} \tag{6d}$$

$$\overline{Nu_L} = \left[Nu_l^6 + Nu_t^6\right]^{1/6} \tag{6e}$$

Ra = Rayleigh number = Gr Pr.

$$\text{Gr} = \text{Grashof number} = \frac{g\,\beta\left(T_s - T_\infty\right)L^3}{\nu^2}$$

$$\text{Pr} = \text{Prandtl number} = \frac{c_p\,\mu}{k} = \frac{\nu}{\alpha}$$

$$\text{Nu} = \text{Nusselt number} = \frac{h\,L}{k}$$

L = characteristic length. For vertical surfaces, it is the dimension parallel to the gravity vector. For horizontal surfaces, it is the total surface area divided by the perimeter of the defined surface.

β = expansion coefficient. ν = kinematic viscosity.
μ = dynamic viscosity. c_p = specific heat capacity.
α = thermal diffusivity. g = acceleration due to gravity.
k = thermal conductivity. h = heat transfer coefficient.

Calculations

The heat transfer coefficient was calculated from the area-averaged horizontal (horiz.) and vertical (vert.) correlations in the following manner:

$$\text{Nu} = \frac{\text{horiz. area}}{\text{total area}}\text{Nu}_{\text{horiz}} + \frac{\text{vert. area}}{\text{total area}}\text{Nu}_{\text{vert}} \qquad (7)$$

The horizontal area was calculated from Width 1 x Width 2. The vertical area was calculated from 2 x Height x Width 1 + 2 x Height x Width 2 (See Table 1). Only one horizontal surface was used in the calculation since a module lying on its side would have only one horizontal surface subjected to natural convection.

The total heat transfer coefficient for test purposes was calculated by pairing Eq. 1 with Eq. 4, Eq. 2 with Eq. 5 and Eq. 3 with Eq. 6. This served to provide a low, medium and high range of convection numbers for evaluation.

Results

The ZT for each module as measured in a vacuum (configuration 1) is shown in Table 3. The Z at 25°C represents the measured Z with temperature correction to 25°C. Table 4 shows the low, medium and high convection coefficients calculated for each module.

Table 3. Z Measured in Vacuum

Module Number	ZT	Z at 25°C (1000/K)	Pressure (Pa)
1	0.790	2.614	3.17
2	0.797	2.673	3.20
3	0.757	2.533	3.37
4	0.785	2.618	3.51
5	0.762	2.521	2.90
6	0.769	2.529	3.28
7	0.891	3.003	2.93

Table 4. Convection Coefficients

Module Number	Low ($W/m^2/K$)	Medium ($W/m^2/K$)	High ($W/m^2/K$)
1	5.9	7.5	7.9
2	5.8	7.2	7.6
3	6.2	7.9	8.4
4	6.2	7.9	8.5
5	7.0	8.8	9.8
6	6.8	8.5	9.4
7	6.2	7.9	8.4

Table 5 shows the results of measuring each module in air (configuration 2) with the corresponding convection coefficient.

Table 5. Z at 25°C Measured in Air

Module Number	[Low] (1000/K)	[Medium] (1000/K)	[High] (1000/K)
1	2.619	2.605	2.610
2	2.632	2.639	2.642
3	2.514	2.525	2.531
4	2.617	2.615	2.615
5	2.491	2.493	2.494
6	2.515	2.522	2.532
7	2.997	3.015	3.015

Figure 3 shows the percent error in measurements of Z at 25°C relative to the vacuum measurements.

Lastly, the Z for module number 4 was tested at various vacuum levels to see what effect the pressure had on measurement. These particular measurements assumed that no gasses were present; only a radiation correction factor was applied. Figure 4 shows how the Z at 25°C varied with vacuum level. A very distinctive trend is evident if the data point located at 15 Pa were excluded as erroneous. Furthermore, the two data points at 4 Pa and 3.5 Pa are nearly identical. Therefore, it may be likely that at pressures below 4 Pa, residual gasses may no longer have any affect on measurements of Z. Unfortunately, the particular vacuum system that was used was not able to achieve a pressure lower than approximately 3 Pa, and the pressure meter did not read

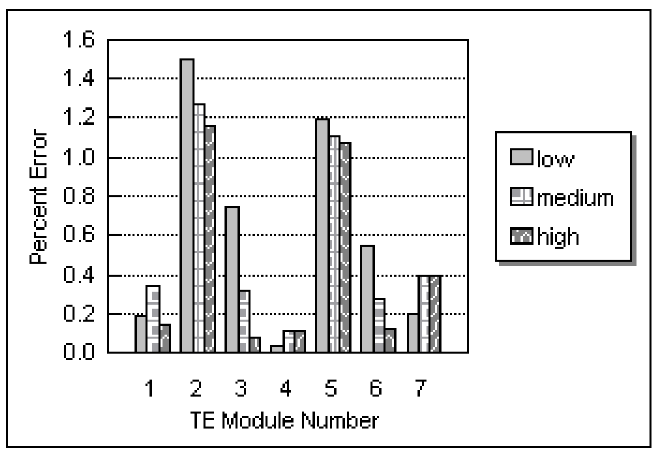

Figure 3. Error in Z at 25°C Relative to Vacuum

above 21 Pa. It was not possible to test for trends beyond these ranges.

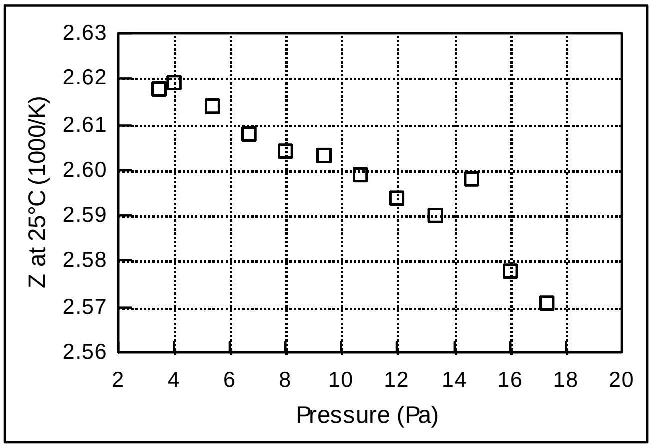

Figure 4. Variance of Z with vacuum level

Conclusions

The convection correlations were effective in providing test results comparable to measurements made in vacuum. However, the low, medium, and high convection coefficients did not provide correspondingly low, medium and high measured Zs 100% of the time. One possible reason for this was that there was an imperfect thermocouple attachment to the module when it was measured in a vacuum. Consequently, the percent errors shown in Figure 3 could themselves be in error since the vacuum measurements formed the basis. Another reason is that there is an inherent uncertainty in all measurements, regardless of what is being measured. Also, as was shown in Figure 4, the residual gasses in the vacuum chamber can still affect the accuracy of measurements, particularly at pressures greater than 4 Pa. Tentatively, at pressures less than 4 Pa, residual gasses did not affect measurements significantly, although more testing at lower pressures would be needed to verify this. Despite these potential sources of error, the high convection coefficients yielded results that were generally closest to the vacuum measurements with an average error of only 0.44%.

The convection coefficient defined by eqs. 3, 6, and 7 should be used when making measurements in air to yield the most accurate results when compared with measurements taken in vacuum. This convection correlation should provide adequate accuracy for quality control testing. However, for critical measurements, testing must still be done in vacuum. The pressure level should be at most 4 Pa for tests done in vacuum.

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