Investigation into the use of Thermoelectric Devices as Heat Source for Heat Sink Characterization

C. K. Loh, Daniel T. Nelson, D. J. Chou
Enertron, Inc
100 W. Hoover Suite 5
Mesa Arizona 85210
Phone: (480) 649-5400
Fax: (480) 649-5434
Email: ckloh@enertron-inc.com

Abstract

Experimentation to characterize the heat sink performance is often performed under different procedures and apparatuses specifically catered to the knowledge of the individual in the thermal testing laboratory. When simulating the heat load of the electronics package, the conventional practice is to use resistance heating elements such as cartridge resistive heaters or flexible thin film heaters. Recently, thermoelectric devices (TED) are also being used as the heat source in heat sink laboratory experiments.

The primary benefit of using a TED as a heat source in laboratory testing is that the TED is a unidirectional heat pump. All input electrical power is discharged to the TED hot side when properly used. This unidirectional heat pump process provides a more conservative experimental result, especially when calculating the experimental heat sink resistance. Contrarily to a TED, the resistance heater is a heat diffusion device, where the heat is dissipated to the surroundings by conduction. Even when the heater is fully insulated on all sides but the heat sink, a portion of heat is still lost to the ambient through the insulation. The effect is less energy passes to the heat sink than is inputted to the resistive heater.

Keywords: thermoelectric device, resistive heating, cartridge heater, experimentation.

Nomenclature

A_{ib}	Iron block area perpendicular to heat flow direction, m^2
A_{str}	Heater structural insulation are perpendicular to the heat flwo direction , m^2
COP	Coefficient of performance
COP_{opt}	Theoretical optimum coefficient of performance
G	Geometric ratio, Area/Length of TED couple, cm
H	Coefficient of heat transfer, W/m^2K
I	Applied current, Amp
I°	Theoretical optimum current, Amp
k_{ib}	Iron block thermal conductivity, W/mK
k_{str}	Structural insulation block thermal conductivity, W/mk
k_{TED}	TED thermal counductivity, W/mK
L_{ib}	Length of the iron block, m
L_{str}	Length of the structural insulation, m
N	Number of thermoelectric couples
Q_{absord}	Heat drawn from cold junction of TED, Watts
Q_f	Heat flow through the iron block, Watts
Q_h	Heat dissipated from the hot junction of the TEC, Watts
Q_{loss}	Heat loss through the polystyrene (styrofoam) insulation, Watts
R	Electrical resistance, Ω
T_{ave}	Average temperarure between hot and cold junction of TEC, °C
T_C	Cold junction temperature, °C
ΔT_{hc}	Temperature difference between hot and cold junction of TEC, °C
ΔT_{ha}	Temperature difference between the heater block and the ambient, °C
ΔT_{ib}	Temperature difference across the iron block, °C
ΔT_{max}	Maximum temperature difference between hot and cold junction of TEC, °C
V	Applied voltage to the TED, V
W_{input}	Applied power, Watts
Z	Figure of merit, K^{-1}
α	Seeback coefficient, V/K
ρ	Resistivity, Ω.cm
Θ_{ins}	Insulation thermal resistance, °C/W
Φ, Φ_{opt}	Grouping variable

Introduction

Thermoelectric devices (TED) have found their way into a variety of cooling applications, ranging from laser diode cooling, infrared sensor cooling, scientific and medical equipment cooling, compact dehumidifier, cool box, and more. Packed with two to hundreds of p and n types of BiTe base semiconductors and utilizing the Peltier cooling principle, the BiTe substrate can transport heat from the semiconductor's cold junction to hot junction without any moving parts.

Though most of the TED applications are associated with localized cooling and temperature control, the TED itself can be used to represent a heat source in laboratory experimentation to characterize a heat sink performance. As opposed to the widely acceptable practice of using resistive heating elements as a heat source, such as cartridge or thin film heaters, the TED is a solid state unidirectional heat pump that requires minimum insulation and produces a greater than or equal heat output when compared with the electrical power input. This produces more conservative experimentation, and often times more accurate experimentation, when compared with traditional resistive heaters.

The goals of this study are as follows:

- Take a closer look between the two devices in terms of their functionality and how they are constructed for experimentation.
- Examine the theoretical foundation that represents the experimentation.
- Prove that the TED can provide higher heat energy than the cartridge heater with the same amount of electrical power input.
- Illustrate the advantages of using a TED to simulate the heat source in heat sink characterization

The remaining part of the paper presents the experimental method, experimental results, theoretical analysis, and finally draws a conclusion based on the experimental results.

Types of Heat Sources

Typically, in a heat sink thermal performance experiment, three different types of heating devices are commonly used to simulate the heat dissipating package or heat source. They are the cartridge heater, flexible film heater and TED. The heaters are part of the electrical resistive heaters family.

Electrical Resistive Heating

Figure 1. Cartridge Heater Schematic

In resistive heating, electrical current is passed through the resistive metal wire or foil and converts electrical energy to heat. The cartridge heater (Figure 1), for example, consists of nickel chromium resistance coil encapsulated inside a stainless steel sheath with the magnesium oxide filler. One end of the sheath is usually sealed, and the other end consists of the electrical terminals for connection to the power source [1]. Cartridge heaters can be purchased through the manufacturer by specifying the radii diameter, the length of the sheath, and the output wattage. When using the cartridge heater, one must pay close attention to matching diameter tolerance between the cartridge heater and the heater block that is used to contain the heating cartridges. In the case of high-wattage-density heaters, holes are drilled within the ±0.001" of the cartridge diameter [2]. To get a good thermal conductive path between heating cartridge and the heater block, thermal grease is usually used to fill up the remaining air void. In a thermal testing laboratory, a high thermal conductivity metal block is needed to house the cartridge heaters along with a sizeable thermal insulation to minimize the heat diffusion from the metal block to the surrounding ambient.

The flexible heater as the name implies, is a semi-rigid thin foil that is bendable and conformable to the shape of the object it is applied onto. The basic operating principle of this heater is the same as the cartridge heater, but instead of using the nickel chromium resistance coil, the heating element is wire-wound or acid etched nickel resistance alloy foil. Figures 2 and 3 shows the schematic of both heaters. As seen in Figures 2 and 3, this fragile heating circuitry is laminated with a thin layer of insulation material such as silicone rubber, kapton (polyimides), or neoprene, to improve the integrity and strength of the overall product. In general, the kapton insulation material is used where high precision heating is required and the assembly is subjected to hostile environment, such as high heat radiation and volatile chemical substances [3]. The silicone rubber insulated flexible heater is suited for general purpose heating where precision is not a constraint. Lastly, the neoprene-insulated heater is designed for low temperatures with low watt density application. When using the flexible heater as a heat source in thermal experimentation, insulation is needed on one side of the heater to minimize heat loss to the surroundings.

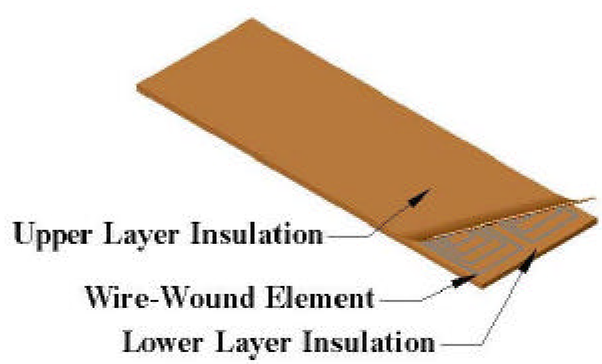

Figure 2. Flexible Heater: Wire-Wound Elements

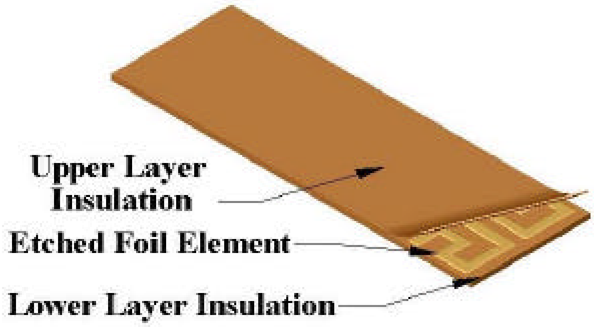

Figure 3. Flexible Heater: Etched Foil Elements

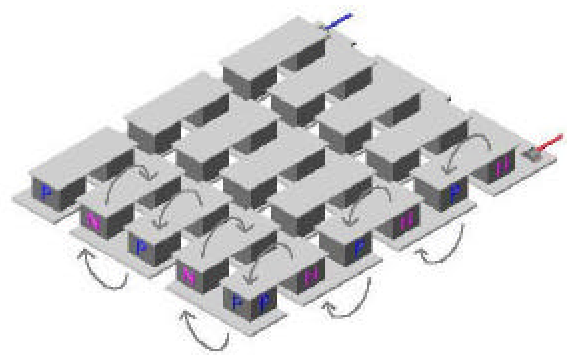

Figure 4. Schematic of Thermoelectric Cooler

Thermoelectric Device

A thermoelectric device is a solid-state energy converter which contains arrays of dissimilar semiconductors (the *n*-types and the *p*-types), thermally joined in parallel and electrically joined in series at both ends to form a couple. The *n*-type semiconductor has excess electrons whereas the *p*-type is electron deficient which converts electrical energy to thermal energy and vice versa. When a TED is converting thermal energy to electrical energy, the module is known as a thermoelectric generator (TEG). Alternatively, when converting from electrical energy to heat pumping energy, the module is called a thermoelectric cooler (TEC). TEG operates on the Seebeck effect, a solid-state theory that explains the current generation through a pair of dissimilar semiconductors due to temperature gradient. This heat engine is relatively inefficient and produces power that is only suited for endurance power generation, such as the electrical source for deep space exploration missions.

TEC operates on Peltier effect, the semiconductors p- and n- couples can be anywhere from a few to several hundreds aligned electrically in series and thermally in parallel between the two ceramic plates. As current passes through the couples, from *n*-type to *p*-type, it creates a temperature gradient across the TEC when heat energy is drawn from the cold junction, transported through the semiconductors by electrons (*n*-type) and holes (*p*-types), and finally, dumps the heat off at the hot junction as shown in Figure 4. If the polarity of the current is reversed, the heat transporting direction reverses accordingly. The Peltier effect is proportional to the current and the temperature gradient across the cooler, and independent of the semiconductor geometry. The Peltier force will encounter two oppositional effects; the Joule heating which is generated by electricity passing through the semiconductors in the present of resistive field, and the heat conducted from the hot junction back to the cold junction. As opposed to the Peltier effect, the two oppositions are irreversible. All these effects are significantly important when evaluating the performance of the thermoelectric cooler.

In order to analyze the performance of the TECs, three main variables of interest have to be considered. They are the coefficient of performance (COP), the heat pumping rate and the maximum temperature difference that the device can produce. In general, for any refrigeration cycles, the system efficiency is determined by the amount of energy the system is capable of absorbing over the total power input to the system, given as:

$$COP = \frac{Q_{absord}}{W_{input}} \tag{1}$$

For the case of TECs, the Q_{absord} is expressed as [4]:

$$Q_{absord} = 2N[\text{á}\, IT_c - \frac{I^2 \text{ñ}}{2G} - k_{TED} G \Delta T_{hc}] \tag{2}$$

Q_{absord} is computed by taking into consideration the heat pumped from the cold junction to the hot junction due to Peltier effect, back flow of heat to the cold junction due to Joule heating and the heat conduction between the two junctions. The sum of these three terms multiplied by the number of couples yields the total amount of heat absorbed from the cold side of the TEC.

The heat dissipated from the hot junction of a TED can be evaluated by:

$$Q_h = 2N[\text{á}\, IT_h + \frac{I^2 \text{ñ}}{2G} - k_{TED} G \Delta T_{hc}] \tag{3}$$

The electrical power applied to the TEC, W_{input}, is the difference between Q_h and Q_{absord}. It is given as:

$$W_{input} = 2N\left(\text{á} I \Delta T_{hc} + \frac{I^2 \text{ñ}}{G}\right) = VI \tag{4}$$

where ΔT is the temperature difference between the hot junction and the cold junction of the semiconductors.

The maximum heat-pumping rate can be found by taking the derivative of (2) with respect to I at zero Q_{absord}, to obtain the optimum current:

$$I^{\circ} = \frac{\text{á}T_c G}{\text{ñ}} \qquad (5)$$

Substituting the (5) back to (2) yields the maximum heat-pumping rate:

$$Q_{max} = GN\left(\frac{\text{á}^2 T_c^2}{\text{ñ}} - 2k_{TED}\Delta T_{hc}\right) \qquad (6)$$

The largest temperature difference occurs when Q_{max} is equal to zero and hence, the maximum temperature difference is given as:

$$\Delta T_{max} = \frac{1}{2}T_c^2 Z \qquad (7)$$

$$Z = \frac{\text{á}^2}{k_{TED}\text{ñ}} \qquad (8)$$

Z is known as the figure of merit. Since Z depends upon the material properties, slight changes in Z will produce significant changes in the COP and thermal efficiency of the TEC.

The optimum COP for TEC is found by introducing a new grouping term, $\Phi = I\rho/\alpha^2 G$, and substitutes into (1):

$$COP = \frac{\Phi T_c - \frac{\Phi^2}{2} - \frac{\text{Ä}T_{hc}}{Z}}{\Phi\text{Ä}T + \Phi^2} \qquad (9)$$

Differentiating (9) with respect to Φ and setting the result equal to zero:

$$\Phi_{opt} = \frac{\text{Ä}T_{hc}}{(ZT_{ave}+1)^{0.5} - 1} \qquad (10)$$

Finally, the optimum COP is obtained by substituting (10) back into (9):

$$COP_{opt} = \frac{1}{\text{Ä}T}\left[\frac{T_c(ZT_{ave}+1)^{0.5} - T_h}{(ZT_{ave}+1)^{0.5} + 1}\right] \qquad (11)$$

The optimum COP in this case, is a measure of the maximum heat pumping capacity of the TEC's from the cold junction to the hot junction.

Experimental Setup

Figure 5 illustrates the experimental setup schematic for cartridge heaters. Three cartridge heaters are inserted into the copper heater block. Thermal grease is applied to the surface of the heaters to fill any remaining air gap between the heater surface and the copper heater block. The whole heater assembly is insulated by a high strength and high thermal insulation material to minimize heat lost to the surrounding area. Moving up along the assembly, a machined tapered aluminum block sits directly on top of the heater. The purpose of this block is to serve as an adaptor to match the two different surface areas between the copper heater block and the NIST iron block. Sitting on the adapter, there is a standard NIST reference machined iron block with known thermal conductivity at any given temperature. The iron block is used here measure temperature within and to calculate the amount of heat given off from the heat source by performing simple conduction analysis. The reason why the NIST iron block was chosen over the commercially available thin film heat flux sensor is due to inaccuracies inherently found in this type of sensor. One of the causes of the inaccuracy is the redistribution of the temperature fields as the heat is passing through the heat flux sensor. In addition, the introduction of heat flux sensor reduces the effective heat transfer coefficient of the whole assembly [5]. Both the aluminum adapter block and the iron block are insulated with a thick layer of polystyrene material. Lastly, a heat sink is placed on top of the iron block to dissipate heat to the environment. Fans are attached to the heat sink to provide forced convection. Figure 5 illustrates the experimental setup.

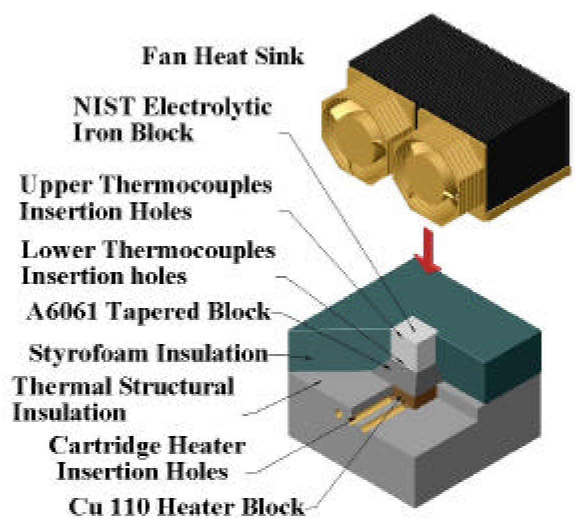

Figure 5. Heater Experimental Setup

The experimental setup for the TEC is depicted in Figure 6. It is similar to the cartridge heater except for two differences. First, there is an aluminum block mounted underneath the cold junction of the TEC for temperature measurements. Second, the TEC is not embedded in thermal structural insulation. Instead, the TEC simply rests on a nylon insulator block. Table 1 provides a list of equipment and apparatus specifications used in the experiment.

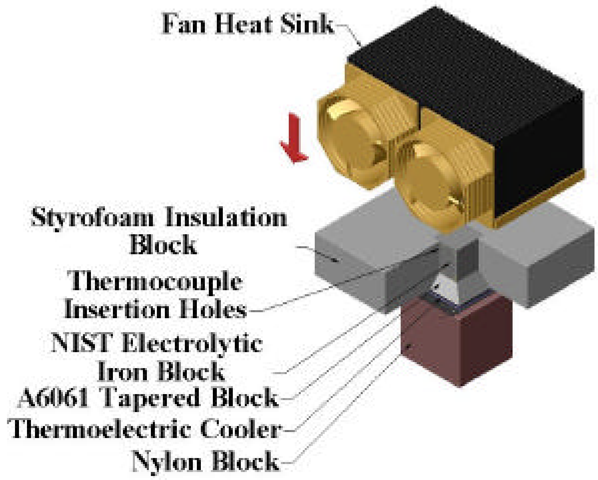

Figure 6. TEC Experimental Setup

Table 1. Description and specification of apparatus and material.

Description	Specification	Dimension	Usage
Cartridge Heater	Max Wattage: 120 Heat Flux: 150W/in^2	0.25”∅x1.5”L	Heat up the Copper heating block.
Copper Heating Block	----	40W x 40L x 15T mm	Simulate heat source
TEC	@27°C Q_{max} = 54 Watts V_{max} = 14.7 Volts ΔT_{max} = 66°C	40W x 40L x 4T mm	Simulate heat source.
Thermal Structural Insulation Block	k = 0.13 W/m·K @ 27°C C_p= 0.28 Btu/°F·lb @ 93°C ρ = 737 kg/m^3	110W x 110L x 50T mm	Prevent heat lost from the Copper-heating block to the surroundings.
Commercially available Styrofoam	k = 0.027 W/m·K	190W x 190L x 23T mm	Insulation to prevent heat lost to the surrounding.
NIST RM 8421 Electrolytic Iron	@ 300K k = 76.4 W/m·K λ = 105.0 nΩ·m	22W x 22L x 23T mm	Standard Reference Material for temperature measurement and heat flux calculation.
Copper Base Heat Sink	Θ = 0.22 °C/W @ 200 FPM	125W x 76 L x 64 H mm	Heat dissipation.
Fan	DC 12V, 0.27 Amp Volumetric Flow rate: 17.5 FM Static Pressure: 4.56 mmH_2O	60W x 60H x 25L mm	Assist convection heat transfer.

Experimental Analysis

The experimental results are compared by using the percentage conversion principle. In here, the percentage heat conversion is defined as the ratio of heat transfer through the iron block over the electrical power input The experimental percentage heat conversion for heater or TEC's can be expressed as:

$$\%\,\text{Conversion} = 100\left(\frac{Q_f}{W_{input}}\right) \tag{12}$$

The heat flow through the iron block, Q_f, is assumed to be the usable heat given off from the heater or the TEC. It is given as:

$$Q_f = \frac{k_{ib} A_{ib} \text{Ä} T_{ib}}{L_{ib}} \tag{13}$$

and W_{input}, would be the power applied to the heater or TEC:

$$W_{input} = VI \tag{14}$$

To further establish a baseline for comparison, the estimated percentage conversion is introduced:

$$\text{Est.}\ \%\,\text{Conversion} = 100\left(\frac{Q_f + Q_{loss}}{W_{input}}\right) \tag{15}$$

Q_{loss}, represents the calculated heat loss to the polystyrene (Styrofoam) insulation as shown in Figure 5 and 6. It can be expressed as:

$$Q_{loss} = W_{input} - Q_f - Q_{str}$$

(16)

where Q_{str} is the heat loss from the structural insulation to the ambient.

$$Q_{str} = \frac{k_{str} A_{str} \text{Ä} T_{ha}}{L_{str}} \tag{17}$$

Since the amount of heat loss to the polystyrene insulation is the same for the heater and the TEC at any given electric input, the value found of Q_{loss} in equation 16 is used for both the heater and TEC calculations.

Discussions of Results

Figure 7 shows the percentage heat conversion of both heater and TEC over the electrical power input. For an ideal condition, the percentage heat conversion should be at 100%, meaning all the electrical power input is converted to heat output.

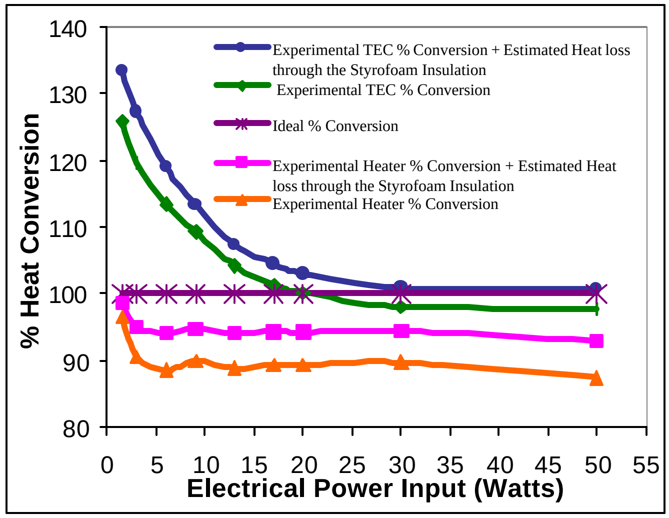

Figure 7. % Heat Conversion vs. Electrical Power Input for Heater and TEC.

Comparing between the experimental percentage heat conversion for both heater and TEC, the TEC has much higher percentage heat conversion over the entire electrical power input range, from 2 Watts to approximately 50 Watts. This is because in the heater assembly, heat is diffused to the heater insulation whereas for TEC, heat is pumped from the cold junction to the hot junction with no diffusion. For lower wattages, a TEC supplies significantly higher heat than is input electrically. The reason is that the COP of 40 x 40 mm TEC decreases as it reaches its maximum rated wattage. Typical maximum rated wattages for 40 x 40 mm TEC is around 30 to 50 Watts. A higher wattage rated or a larger size TEC can be used to supply a higher wattage if necessary. In addition, in this experiment, the addition of NIST iron block and aluminum-tapered block causes greater heat loss to the insulation. In an actual heat sink experiment, the heat sink is directly attached to the heat source without the Styrofoam insulation and iron block. Hence, there is no heat loss from the iron block and the Styrofoam insulation.

Figure 7 also shows the trend of the experimental percentage conversion plus the estimated heat lost through the Styrofoam insulation for both devices. When the amount of heat lost to the insulation is added to the total heat converted, the experimental percentage heat conversion increases. These curves reflect the actual experimental environment, in the absence of the iron block and tapered block. They show that the TEC produces more usable heat over the heater when assuming the same amount of heat is lost through the Styrofoam insulation, Q_{loss}. In addition, using TECs as the heat source in heat sink performance testing would yield more conservative results compared to the heater as the TEC percentage conversion plus the estimated heat lost to the Styrofoam curve stays above the ideal conversion line over the entire electric power input range. Furthermore, in our test setup, the TEC also gave more accurate results in the range of 13-50 Watts. In order to get the heater to operate at the 100% ideal line, guard heaters have to be used. A guard heater is used to increase the temperature of the insulation surrounding resistive heater to the same level as the resistive heater. This in effect, prevents heat transfer from the resistive heater to the insulation, thus allowing only heat transfer from the resistive heater to the heat sink. However, controlling and maintaining the amount of heat output from the guard heater itself is an additional control task.

At low wattages range, the percentage conversion of the TEC increases exponentially. This is because the COP of the TEC plays an important role in deciding the heat output from the hot junction of the TEC in this low wattage range. Typically, when using a TEC for laboratory heating purposes, it is recommended that the TEC is operating at around 20% to 100% of the manufacturer rated wattage. Alternatively, when performing lower wattage experiments, a lower power TEC is recommended for use as a heat source.

Conclusions

Experimental results have shown that using a TEC in heat sink thermal performance characterization yields more conservative results because the amount of heat transferred to the heat sink by the TEC is closer to the actual amount of electrical power inputted into the TEC. Furthermore, in our experimentation, the amount of heat transferred to the heat sink by the TEC gave a more accurate result in the range of approximately 25-100% of the TEC's maximum rated voltage. TECs are easy to obtain and are available in a large number of sizes and maximum wattages. TECs are also easy to use for experimentation in that they do not require base structural insulation. For this reason, they take less time to setup for exp erimentation as compared to cartridge heaters. In lab environment, the use of guard heaters or other countermeasures in conjunction with resistance heaters is necessary for minimizing the heat loss through the structure insulation and therefore increasing the accuracy of heat output of resistance heaters. Though this requires additional control, effort and skill. The use of a TEC as the heat source should be considered as an option to thermal engineers.

References

[1] Erickson, C. James, *Handbook of Electrical Heating for Industry*, 1st Edition, IEEE Press, New York, 1995.

[2] Omega Engineering, *The Electric Heaters handbook*, Volume MM, Stamford, Connecticut, USA, 2000.

[3] Watlow, *Watlow Heaters Catalog*, St. Louis, Missouri, USA, 2000.

[4] Angrist, Stanley W., *Direct Energy Conversion*, 4th Edition, Allyn and Bacon, Inc., Boston, 1982.

[5] Lasance, Clemens J.M., "The Conceivable Accuracy of Experimental and Numerical Thermal Analyses of Electronic Systems", *Proceedings of 17th IEEE Semiconductor Thermal Measurement & Management Symposium*, pp. 180-198, San Jose, CA, March 20-22, 2001.