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Module Design and Fabrication

Raymond Marlow and
Edward Burke
Marlow Industries
Dallas, Texas U.S.A.

46.1 Introduction

Thermoelectric refrigeration is a versatile technology that can be customized to meet the needs of a wide range of customers. This flexibility comes from the options available in the design and also fabrication of the thermoelectric module. The following chapter reviews the details involved in the design and fabrication of thermoelectric refrigeration modules.

46.2 General Theory of Operation

Thermoelectric refrigeration is achieved when a direct current is passed through one or more pairs of n- and p-type semiconductor materials.' Figure 1 is a diagram of a single pair consisting of n- and p-type semiconductor materials. In the cooling mode, direct current passes from the n- to the p-type semiconductor material. The temperature T_c of the interconnecting conductor decreases and heat is absorbed from the environment. This heat absorption from the environment (cooling) occurs when electrons pass from a low energy level in the p-type material through the interconnecting conductor to a higher energy level in the n-type material. The absorbed heat is transferred through the semiconductor materials by electron transport to the other side of the junction T_H and liberated as the electrons return to a lower energy level in the p-type material. This phenomenon is called the Peltier effect.

A second phenomenon is also important in thermoelectric refrigeration. When a temperature differential is established between the hot and cold sides of the semiconductor material, a voltage is generated. This voltage is called the Seebeck voltage, and it is directly proportional to the temperature differential. The constant of proportionality is referred to as the Seebeck coefficient.

The Peltier effect is controlled by the Peltier coefficient, defined as the product of the Seebeck coefficient of the semiconductor material and the absolute temperature. The Peltier coefficient

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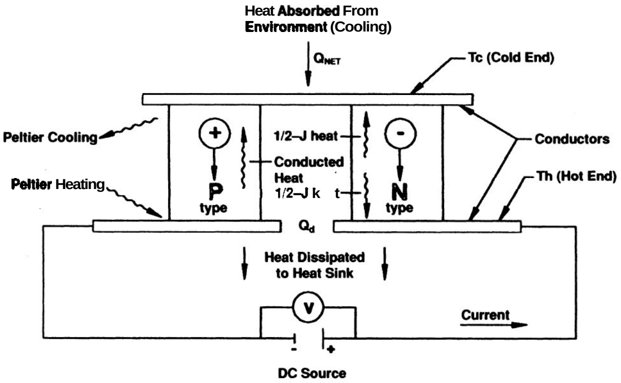
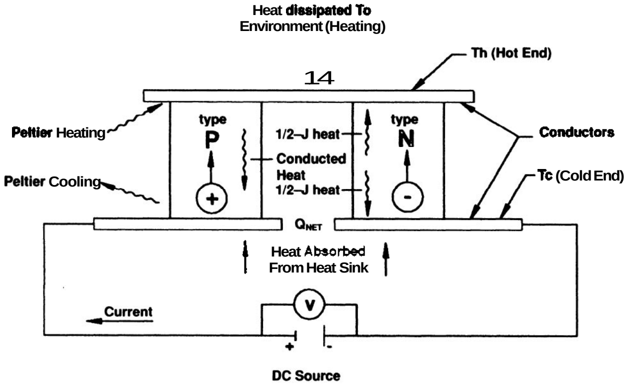


(a): Cooling



(b): Heating

FIGURE 1 Thermocouple.

relates to a cooling effect as current passes from the n-type material to the p-type material, and a heating effect when current passes from the p-type material to an n-type material, as shown in Figure 1. Reversing the direction of the current reverses the temperature of the hot and cold sides.

$$Q_{net} = \alpha T_c I - \frac{1}{2}(I^2R) - K\,\Delta T \qquad (1)$$

where Q = rate of heat absorbed at cold junction, in watts; a $= \alpha_{pn} = \alpha_p - \alpha_n$ = the difference between the absolute Seebeck coefficient of the p and n materials; AT = $(T_h - T_c)$ operating temperature difference, degrees Celsius; T_h = hot junction temperatures, Kelvin; T_c = cold junction temperature, Kelvin; R = $R_n + R_p$ electrical resistances of the couple legs per degree Celsius and K the thermal conductance.

Ideally, the amount of heat absorbed at the cold side and the heat dissipated at the hot side are dependent on the product of the Peltier coefficient and the current flowing through the semiconductor material. Practically the net amount of heat absorbed at the cold side due to the Peltier effect is reduced by two sources, conducted heat and Joule heat. Due to the temperature differential between the cold and hot sides of the semiconductor material, heat will be conducted through the semiconductor material from the hot to the cold side. As the current is increased, the temperature differential, and thus the conducted heat, increases because the Peltier cooling effect increases. When a steady state is established at the cold junction, the Peltier cooling equals the heat conducted down the couple legs, plus heat absorbed (useful heat pumped).

As the current continues to increase and Joule heating becomes the dominating factor, a point is reached where additional current will result in less net cooling. The current at which no further

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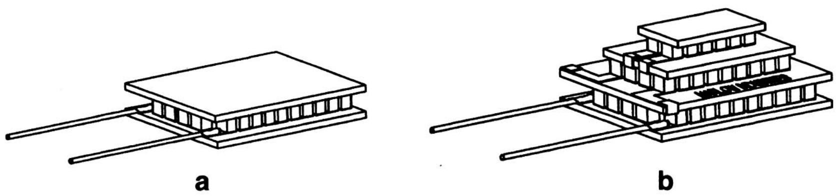

FIGURE 2 **Typical thermoelectric module designs: (a) single-stage module, (b) multistage module.**

cooling can be achieved is the maximum current (I„,). Maximum voltage ($V_{\max}$) and maximum temperature differential AT„ will also occur for any given heat load at the maximum current.

The net heat dissipated at the hot side is the sum of the net heat absorbed at the cold side plus the applied electric power. The coefficient of performance (COP) used to define the cooling "efficiency" is defined as the net heat absorbed at the cold side divided by the applied electric power.

The properties of semiconductor materials-electrical resistivity, thermal conductivity, and Seebeck coefficient—that define their maximum cooling capabilities are temperature dependent. This is why simple formulas are not dependable for thermoelectric refrigeration design. For any one semiconductor material there is a temperature range over which that particular material has the best performance. The most widely used thermoelectric material for refrigeration in the temperature range of −184 to 446°F (−120 to 230°C) is a pseudo-binary alloy, $(Bi,Sb)_2(Te,Se)_3$, commonly referred to as bismuth telluride.

The refrigeration capability of a semiconductor material is dependent on a combined effect of the material's Seebeck voltage, electrical resistivity, and thermal conductivity over the operational temperature range between the cold and hot sides. The expression that contains these material parameters is referred to as the figure-of-merit, and is denoted by Z (in reciprocal Kelvin)

$$Z = \frac{\alpha^2}{\rho\lambda}$$

Each of the n- and p-type semiconductor material properties varies as a function of temperature, and therefore the figure-of-merit for each material is temperature dependent. It can be shown that the maximum temperature differential that can be achieved by a single pair of n- and p-type materials is directly proportional to the "temperature averaged" figure-of-merit of each semiconductor material. Therefore, maximizing the figure-of-merit is the major objective in the selection and optimization of thermoelectric materials. The figure-of-merit of the semiconductor material limits the temperature differential, whereas the length-to-area ratio of each n- and p-type semiconductor material defines the heat pumping capacity.

46.3 Description of a Thermoelectric Refrigeration Module

More than one pair of semiconductors are usually assembled together to form a thermoelectric module. Within the module each semiconductor is called an element, and a pair of elements is called a thermocouple. Thermoelectric modules, as shown in Figure 2, are typically classified as single-stage modules or multistage modules.

Single-Stage Module

A single-stage module as shown in Figure 2a consists of several thermocouples connected thermally in parallel and electrically in series to increase the operating voltage of the module. These thermocouples are interconnected with good electric conductors such as copper. The conductors must be electrically isolated from the device being cooled; otherwise the module will be electrically short-circuited to the surface being cooled. However, the electrical isolation material must also be thermally conductive material to minimize the temperature difference between the conductor and the device being cooled. The module shown in Figure 2a has a ceramic plate on the top and bottom surfaces of the module. Alumina ceramics typically provide the electrical isolation and thermal

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conductance that satisfy this requirement. Beryllium oxide ceramics may also be used where maximum lateral heat transfer is desired such as in multistage coolers (Figure 2b).

Thermoelectric modules vary in size from a single pair of elements that may be as small as 0.06 in? (1.5 mm^2) up to groups of pairs that may be 2.0 in? (51 mm^2). The limit in making smaller modules is related to the assembly of smaller pellets and the mechanical integrity of the pellets.

A limiting factor in the use of single-stage modules is related to the figure-of-merit of the semiconductor material. Regardless of the amount of power applied to a single-stage module, the coldest temperature that can be reached with bismuth telluride with a hot-side temperature of 80°F (27°C) and no thermal load is approximately –29°F (–34°C) in still air and –53°F (–47°C) in a vacuum.

Multistage Module

When the desired temperature differential cannot be obtained with a single-stage module, a multistage module is required. A typical three-stage module is shown in Figure **2b.** Multistage modules are essentially single-stage modules stacked in a vertical array. Typically a multistage module is pyramid shaped because the lower stage must pump the heat dissipated by the upper stages in addition to the active heat load on the top stage. Therefore, there are always more pellets in the lower stage than in the upper stages when all of the pellets are connected in series.

As additional stages are added to a module, colder temperatures can be achieved. A practical limit in the number of stages is presently between eight and ten stages. With an eight-stage module, a temperature of –218°F (–139°C) on the cold side has been achieved when the hot-side temperature was 127°F **(53°C).**[2]

46.4 Operational Characteristics

The basic operational characteristics of a thermoelectric module include the cold-side and hot-side temperatures, heat pumping capacity at the cold side, heat dissipated at the hot side, input current, and voltage. The acceptable range of each of these characteristics must be established by the design engineer in order to select a commercial thermoelectric module. Considerations in the final selection are typically performance, cost, and reliability.

Number of Stages

The first consideration in the selection of a module is to determine the number of stages required to obtain the desired temperature differential, which is defined by the desired cold- and hot-side temperatures. The temperature differential that is achievable for various modules depends on the atmosphere in which the module operates. A greater temperature differential can be reached when the module is operating in a vacuum compared with operation in dry air, nitrogen, or other gases because the passive heat load is less in a vacuum. Figure 3 shows the practical cold-side temperature range achievable with present thermoelectric materials for various numbers of stages in dry nitrogen and vacuum. Figure 3 also shows an overlap in the number of stages of a module relative to the desired temperature differential. This is an important design consideration since, in general, the cost of a module is influenced by the number of stages. As the number of stages increases, the cost of the module increases. For minimum cost, the modules with the fewest number of stages would normally be selected.

The design of multistage modules is complex. Typically multistage modules are custom designed for optimum performance in a specific application. Computer programs to assist in the design of complex multistage modules have been developed and applied by thermoelectric module manufacturers.

Temperature Differential and Heat Load

Manufacturers of thermoelectric modules provide tables that define the maximum performance capabilities of various modules. A typical format is shown in Table 1. The heat pumping capacities

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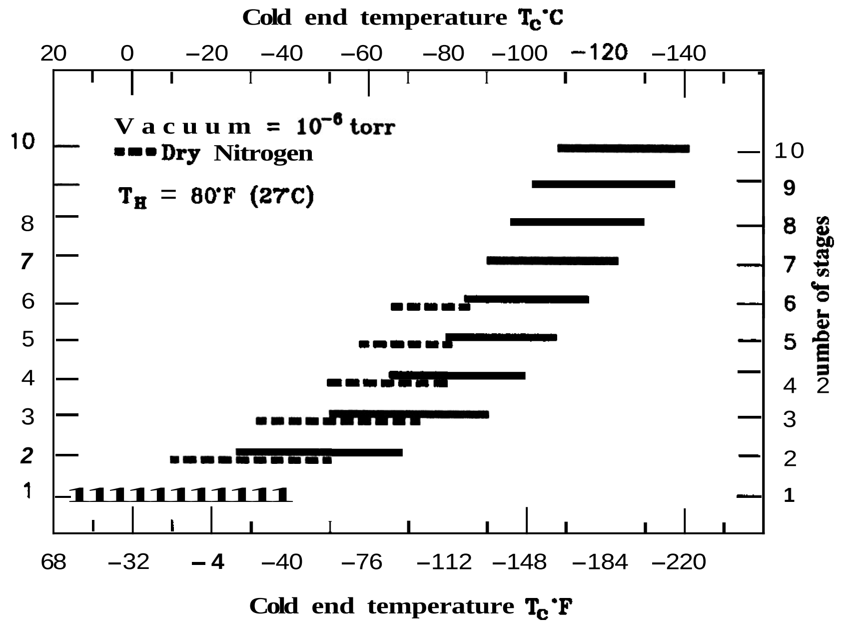

FIGURE 3 Typical performance range of thermoelectric modules.

Table 1 Summary Performance and Geometry of Typical Thermoelectric Cooling Modules

	ΔT_{max} when Q = 0 and T_H = 80.6°F (27°C)							Dimensions				
	Vacuum 10^{-6} torr		Dry N_2 760 mm Hg					Base Ceramic		Top Ceramic		
Module	°F	(°C)	°F	(°C)	Qmax W	Imax A	Vmax V	Width in(mm)	Length in(mm)	Width in(mm)	Length in(mm)	Height in(mm)
1	121	(67)	110	(61)	0.52	1.0	0.8	0.16 (3.96)	0.16 (3.96)	0.16 (3.96)	0.16 (3.96)	0.10 (2.41)
2	122	(68)	115	(64)	2.45	2.0	2.0	0.26 (6.60)	0.26 (6.60)	0.26 (6.60)	0.26 (6.60)	0.09 (2.20)
3	122	(68)	115	(64)	55.4	6.0	15.2	1.50 (38.1)	1.50 (38.1)	1.50 (38.1)	1.50 (38.1)	0.17 (4.40)
4	162	(90)	151	(84)	1.04	1.5	2.1	0.26 (6.60)	0.26 (6.60)	0.16 (3.96)	0.16 (3.96)	0.15 (3.80)
5	193	(107)	176	(98)	6.29	4.7	7.4	0.86 (21.72)	1.11 (28.27)	0.34 (8.61)	0.51 (12.98)	0.44 (11.10)
6	200	(111)	157	(87)	0.85	1.1	6.9	0.52 (13.26)	0.68 (17.22)	0.16 (4.06)	0.31 (7.98)	0.35 (8.80)
7	238	(132)	194	(83)	0.66	3.8	6.5	0.86 (21.72)	1.11 (28.27)	0.20 (5.08)	0.20 (5.08)	0.80 (21.10)

of various modules cover a wide range. The maximum heat pumping capacity is defined as the amount of heat required to suppress the temperature differential to zero. By dividing the maximum temperature differential that can be achieved with no heat load by the maximum heat pumping capacity with no temperature differential, the slope of the temperature differential vs. heat load line can be defined. The actual performance is such that the temperature differential suppression is linear with the heat load.

Performance Curves

After one or more candidate modules have been selected based on data similar to those in Table 1, more detailed performance characteristics need to be considered. Typical module performance

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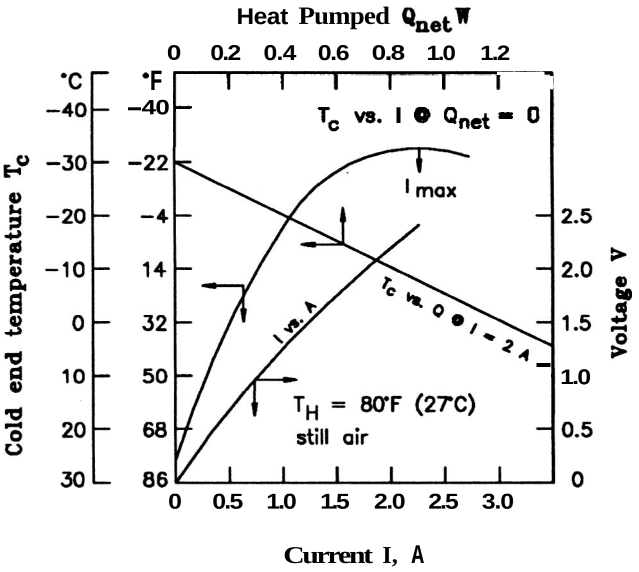

FIGURE 4 Thermal and electrical performance of typical thermoelectric modules.

curves are illustrated in Figure 4. One curve shows the effect of cold-side temperature T_c as a function of current I when the net heat load is zero ($Q_{net} = 0$). As discussed in the next paragraph, the condition of zero net heat load actually includes several parasitic heat loads that are present during the testing of a module. For single-stage modules the tests are normally conducted in room air conditions; for multistage modules they are typically conducted in a vacuum.

The relationship between the cold-side temperature and the net heat pumping capacity when operating at a maximum current is also given in Figure 4. As the heat load is increased, the temperature differential that can be achieved is decreased. The net heat pumped Q_{net}, defined in the performance curve, is the net heat load of the device being cooled. If the device being cooled is a small electrical component, the net heat load consists of the active Joule heating 1^2R within the component and the heat conducted through the lead wires. The parasitic heat loads attributed to thermal radiation and convection on the lateral surfaces of the module are accounted for in the zero net heat load condition. Radiation and convection heat loads will need to be determined when the device being cooled has large surfaces.

The third curve in Figure 4 relates the input voltage to the input current. As the current increases, the voltage increases. The current is not linearly proportional to the voltage due to the temperature dependence of the material properties.

Design Options

There are three usual objectives in the design and application of thermoelectric modules: (1) maximum heat pumping, (2) maximum COP, and (3) maximum speed of response. Maximum heat pumping requires the module to operate at the current and voltage that pumps the maximum amount of heat over the specified temperature differential. The currents and voltages listed in Table 1 apply to operation at the current for maximum heat pumping.

The current for operation at the maximum COP is generally less than the current for maximum heat pumping. For example, when operating at the current for achieving maximum COP at a hot-side temperature of 80°F (27°C), the maximum COP is about 0.2 for a 104°F (40°C) temperature differential. When the temperature differential is 72°F (22°C), the maximum COP is about 1.0.

The design of a module for maximum speed of response is more complex. Consideration must not only be given to the thermal and electrical characteristics of the module, but also to the thermal mass of the module and the device being cooled. In addition, the characteristics of the heat sink

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must be considered in the overall design. Temperature differentials of 144°F (80°C) from a hot-side temperature of 140°F (60°C) have been achieved in less than 2 s for properly designed modules with minimized heat loads. Typical single-stage or multistage modules will achieve the maximum cold-side temperature within 60 to 90 s after power is applied. This response time applies to the cold side of the module when there is no added mass on the cold side and the hot side is attached to a heat sink capable of absorbing the heat with a minimum rise in temperature.

Mechanical Dimensions

The dimensional characteristics of typical modules are shown in Table 1. Typically the top and bottom surface areas of a single-stage module have the same dimensions except for ledges for electrical connections on some modules. The cold-stage surface area of a multistage module is typically smaller than the hot-stage surface area.

The flatness of the cold and hot surfaces of a module, the parallelism between the cold and hot surfaces, and the tolerances on the height of the module are important mechanical characteristics of the modules. These tolerances become increasingly important to overall performance when groups of modules are sandwiched between two heat exchangers and these tolerances are typically ± 0.001 in. or less.

Electrical Characteristics and Control

Table 1 shows the maximum direct current together with the voltage that will achieve the maximum temperature differential in the cooling mode. For maximum performance the ripple component of the direct current should not exceed 10%.

Depending on the direction and the amount of current, thermoelectric modules have the ability to cool, heat, or stabilize temperatures regardless of whether or not the cold surface is above or below the ambient temperature. By applying the correct amount of current at the desired polarity, the temperature of a device can be stabilized as the ambient temperature oscillates. Temperature stability depends on the thermal mass and heat load capacity. Tolerances off 0.18 to ± 0.54°F (± 0.1 to ± 0.3°C) at a stabilized temperature are reasonable.

The module with the lowest current would normally be selected because it makes the power supply temperature controllers less expensive for a given output power. However, the total power to the module is the major factor. Low-current modules will, therefore, require higher voltages to maintain the same power input. High-voltage modules require a larger number of pellets, thereby increasing the cost of the module. Therefore, when selecting a module, a tradeoff is made between module cost and power supply or temperature controller cost, or both.

46.5 Practical Considerations

Thermal

The practical heat load (pumping) for thermoelectric modules ranges from a few milliwatts to tens of watts. This practical limitation is related to the competitiveness of other refrigeration methods in both cost and efficiency. Conventional mechanical refrigeration systems are normally not competitive with thermoelectric refrigeration when the heat loads are under 25 W. Thermoelectric refrigeration can be used to pump heat loads much greater than 25 W, but these are usually for very specialized applications.

The lowest practically achievable temperature is about −148°F (−100°C). Since the efficiency of a thermoelectric module (single-stage or multistage) decreases as the temperature decreases, the heat pumping capacity is typically limited to only a few milliwatts at those cold temperatures.

In heating applications, the practical limit is about 176°F (80°C). This temperature limit is imposed primarily by the manufacturing techniques used to assemble the thermoelectric modules. Although typical thermoelectric modules are assembled at soldering temperatures of 280°F

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(138°C), they are not capable of operating at these higher temperatures for extended periods of time without degrading in performance. The gradual degradation in performance with time is due to contaminants diffusing into the thermoelectric material resulting in changing cooling properties. It should be noted that much less input power is required to heat than to cool.

Environmental

Because thermoelectric modules are solid-state and have no moving parts, high reliability is an inherent feature. However, the reliability may be affected by environmental extremes.

Moisture

With power applied to the module, excessive moisture within the module can cause galvanic corrosion at the thermoelements, solders, and conductors. The moisture can also provide an electric short-circuit within the module, which would reduce the module's performance. Generally, a moisture barrier, gasket, or dry atmosphere is required to maintain reliability.

High Temperature

Continual operation at high temperatures accelerates thermal diffusion of metal ions into the pellets, thus decreasing the performance of the module. In addition, high temperature can cause the solder to migrate into the pellets, which results in a damaged joint, thereby reducing performance. Typically, this is not a problem below 176°F (80°C). However, the temperature at which these factors begin to affect the performance of specific modules should be defined to the design engineer by the module manufacturer.

Thermal Cycling

Rapid temperature cycling from cool to hot can also affect the performance of the module over time. As temperatures change, the module will expand or contract. This action stresses the pellets in the module. Although one major feature of thermoelectric modules is the ability to heat and cool, consideration should be given to minimizing rapid power cycling.

Mechanical Stress

Mechanical stresses applied during shock or vibration are not a major failure mode if the modules are properly mounted. In general, the module is strongest in the compression mode. The most likely failure mode of the solder joints is in the shear direction, which is parallel to the top or bottom surfaces of the module. Most modules will withstand shock levels of 1000 g over a frequency range of 10 to 2000 Hz and random vibration of about 65 g rms from an acceleration power density of 0.01 to 5.0 g^2 Hz over a frequency range 50 to 20,000 Hz.

Vacuum

A vacuum is the most reliable environment in which to use a module. Thermoelectric modules are not susceptible to failure as the result of any level of vacuum. When in a vacuum, the effective heat pumping capacity of the module is increased, thereby providing colder operating temperatures as compared to operating in air for the same input power.

Radiation

No form of radiation has been noted in the literature that has induced failure of thermoelectric modules. Several tests have demonstrated that high neutron bombardment and gamma radiation do not affect performance.

Installation

Mounting

The module may be pretinned and soldered to a heat sink. Usually the hot side is soldered to the heat sink and the cold side is greased with a nonsetting thermal compound for good heat transfer.

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Table 2 Applications of Thermoelectric Modules

Electronic Components	Small Refrigerators	Instruments	Special
Infrared detectors	Boats	Dew point sensor	Dehumidifiers
Laser diodes	Mobile homes	Cold bath	Water coolers
Charge-couple devices	Offices	0°C reference source	Air-conditioning
Blackbody reference source	Hotels	Microtome	Display cabinets
Voltage reference source	Portable picnic boxes	Blood coagulator	Cream coolers

Soldering the top or bottom to a heat sink can lead to mechanical breaking of the thermal expansion mismatch between the module and the attached heat sink is large. This is especially true if the hot and cold sides are both mechanically constrained between the heat sinks.

A good thermal epoxy is another way of bonding or attaching the module. The same failure modes as for soldering also apply to epoxy. Another way of mounting a module is between two clamped plates. Extreme caution should be used for small or multistage modules. Improperly applied compression loads can cause very large shear loads, which will fracture the pellets.

The reason individual modules are not larger than about 2.0 in.^{2} (51 mm^2) is due to mechanical considerations. The modules tend to bow much like a thermostatic bimetallic element. This bowing between the hot and cold sides of the module is due to the fact that one side is contracting and the other side is remaining constant or expanding. The stress induced by these expansion coefficients tends to strain the individual pellets on the outer edge of the module. When the distance across the module increases beyond about 2.0 in. (51 mm), the strain can be too great for the pellets and they crack or break. For this reason, groups of modules are assembled onto heat exchangers rather than mounting one large module to the heat exchangers.

Handling

The module is a rigid assembly sandwiched between ceramic plates. The lead wires are attached to stiff lead conductors. Excessive torque on the lead wires will result in pulling the wires loose or snapping the lead conductor loose from the circuit. The ceramic plates on the top and bottom of the module may be cracked or broken by mishandling, which increases the probability of electric short circuits.

Heat Sinking

Adequate heat sinking is required to dissipate the heat load and power of the module without an excessive hot-side temperature rise. Failures have occurred where the solder joints on the hot side of the pellets were melted because of inadequate heat transfer to the heat sinks.

46.6 Range of Applications

The application of thermoelectric modules ranges from the cooling of electronic components such as infrared detectors with heat loads in the milliwatts and temperatures of −171°F (−113°C) to special applications where 5 tons of air-conditioning is achieved in a railroad passenger car with a temperature difference of 11°F (6°C).[3] Table 2 shows a list of typical applications for thermoelectric refrigeration.

46.7 Thermoelectric Module Fabrication

Thermoelectric modules consist of pairs of p- and n-type semiconductor elements that are electrically connected in series. The electrical circuit is accomplished by soldering the elements to electrical conductors. There are several methods to fabricate the individual components and overall assembly of thermoelectric modules.

Thermoelectric Elements

Thermoelectric p- and n-type elements can be fabricated by a variety of methods. The most common methods utilized by the thermoelectric industry are zone refining, Bridgman method,

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and press and sintering. Most thermoelectric cooler manufacturers utilize a barrier material such as nickel applied to the sides of the elements to allow protection from diffusion of copper and solder constituents into the element and also this barrier provides a surface that can easily accept solder to insure good reliable solder joints. The thermoelectric elements are produced by slicing wafers from the ingot and then subsequently dicing the wafers into the individual elements. Tight dimensional tolerances (± 0.0005 in.) must be held to allow reliable fabrication and also to maintain the design integrity.

Ceramics

Ceramics (alumina, beryllium oxide) are used in the construction of thermoelectric modules due to their good thermal conduction and electrical isolation properties. The copper conductors can be affixed to the ceramics by a variety of methods. The most common method is to print and fire a circuit pattern using molymanganese or copper. The copper conductors are then soldered to this circuit pattern. Ceramics are produced in a variety of shapes, sizes, and such specialty features as holes.

Assembly

The fabrication of the module begins by loading the individual p- and n-type elements into a holding fixture. Special care is required to insure that no elements are misloaded, since this will result in a heater being produced instead of a cooler. The elements are then soldered to the electrical conductors. The solders that are most commonly used are bismuth tin (58% Bi/42% Sn; MP = 138°C), and tin lead (63% Sn/37% Pb; MP = 183°C). Various methods for solder reflow are utilized and range from manual soldering to vapor-phase reflow. Multistage coolers are constructed by assembling each individual stage and then soldering each subsequent stage on top of the next. All modules are then thoroughly cleaned to insure removal of all flux residue.

Testing

A variety of tests can be performed to understand the performance of each module and to insure their high reliability. A typical test sequence is as follows:

- Resistance measurement (AC resistance)
- Vacuum bake (T = 100°C, 2 h)
- Thermal cycle (0 to 100°C; 20 cycles)
- Performance test ($I = I_{max}$; $T_H = 27$°C)
- Resistance measurement

The performance test consists of heat sinking the module to a temperature-controlled surface, then applying power to the module at the "maximum" current and then measuring the temperature of the cold-side ceramic. Testing is best performed in a nitrogen or vacuum environment to minimize the forming of frost/ice on the top of the module. Performance testing can also be performed using a "transient" method that measures the Seebeck voltage and calculates the individual module's performance. The "transient" method requires a high-speed computer and special data acquisition software.[4]

46.8 Summary

Thermoelectric refrigeration is a highly reliable and practical method of cooling electronic components and small-volume refrigerators from a cost and efficiency viewpoint. When heat loads are less than 25 W and temperature requirements are not below −148°F (−100°C) or above 176°F (80°C), thermoelectric refrigeration is practical for a wide variety of applications. There are many

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important considerations that need to be considered when designing thermoelectric coolers, but when properly analyzed will yield a product that can be optimized for a very wide variety of specific applications. Thermoelectric module fabrication and installation require tight tolerances and knowledge of the important process parameters, but with these considered will produce a very reliable, uncomplicated system.

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