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Principles of Direct Thermoelectric Conversion

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1. Introduction

The aim of this chapter is to present some fundamental aspects of the direct thermoelectric conversion. Thermoelectric systems are solid-state heat devices that either convert heat directly into electricity or transform electric power into thermal power for heating or cooling. Such devices are based on thermoelectric effects involving interactions between the flow of heat and electricity through solid bodies. These phenomena, called Seebeck effect and Peltier effect, can be used to generate electric power and heating or cooling.

The Seebeck effect was first observed by the physician Thomas Johann Seebeck, in 1821, when he was studying thermoelectric phenomenon. It consists in the production of an electric power between two semiconductors when submitted to a temperature difference. Heat is pumped into one side of the couples and rejected from the opposite side. An electrical current is produced, proportional to the temperature gradient between the hot and cold sides. The temperature differential across the converter produces direct current to a load producing a terminal voltage and a terminal current. There is no intermediate energy conversion process. For this reason, thermoelectric power generation is classified as direct power conversion.

On the other hand, a thermoelectric cooling system is based on an effect discovered by Jean Charles Peltier Athanasius in 1834. When an electric current passes through a junction of two semiconductor materials with different properties, the heat is dissipated and absorbed.

This chapter consists in eight topics. The first part presents some general considerations about thermoelectric devices. The second part shows the characteristics of the physical phenomena, which is the Seebeck and Peltier effects. The third part presents the physical configurations of the systems and the next part presents the mathematical modelling of the equations for evaluating the performance of the cooling system and for the power generation system. The parameters that are interesting to evaluate the performance of a cooling thermoelectric system are the coefficient of performance (COP), the heat pumping rate and the maximum temperature difference that the device will produce. It shows these parameters and also the current that maximizes the coefficient of performance, the resultant value of the applied voltage which maximizes the coefficient of performance and the current that maximizes the heat pumping rate. To evaluate the power generator performance it is presented the equations to calculate the efficiency and the power output, as well as the operating design that maximizes the efficiency, the optimum load and the load resistance that maximizes the power output. The last part of the chapter presents the selection of the proper module for a specific application. It requires an evaluation of the total system in

which the thermoelectric module will be used. The overall system is dynamic and its performance is a function of several interrelated parameters, such as: the operation temperatures, the ambient temperature, the available space, the available power, among others. Finally it presents conclusions, acknowledgment and references.

Thermoelectric modules consists of an array of p -type and n -type semiconductors elements that are heavily doped with electrical carriers. The elements are arranged into an array that is electrically connected in series but thermally connected in parallel. This array is then affixed to two ceramic plates, one on each side of the elements, that is, one covers the hot joins and the other covers the cold one.

Thermoelectric devices offer several advantages over other technologies: the absence of moving components results in an increase of reliability, a reduction of maintenance, and an increase of system life; the modularity allows for the application in a wide-scale range without significant losses in performance; the absence of a working fluid avoids environmentally dangerous leakages; and the noise reduction appears also to be an important feature.

Applications for thermoelectric modules cover a wide spectrum of product areas. These include equipment used by military, medical, industrial, consumer, scientific/laboratory, and telecommunication's organizations. It includes a range from simple food and beverage coolers for an afternoon picnic to extremely sophisticated temperature control systems in missiles and space vehicles. Typical applications for thermoelectric modules include: avionics, calorimeters, cold chambers, cold plates, compact heat exchangers, constant temperature baths, dehumidifiers, dew point hygrometers, electronics package cooling, environmental analyzers, heat density measurement, immersion coolers, integrated circuit cooling, infrared detectors, infrared seeking missiles, microprocessor cooling, power generators, refrigerators and on-board refrigeration systems (aircraft, automobile, boat, hotel, among others).

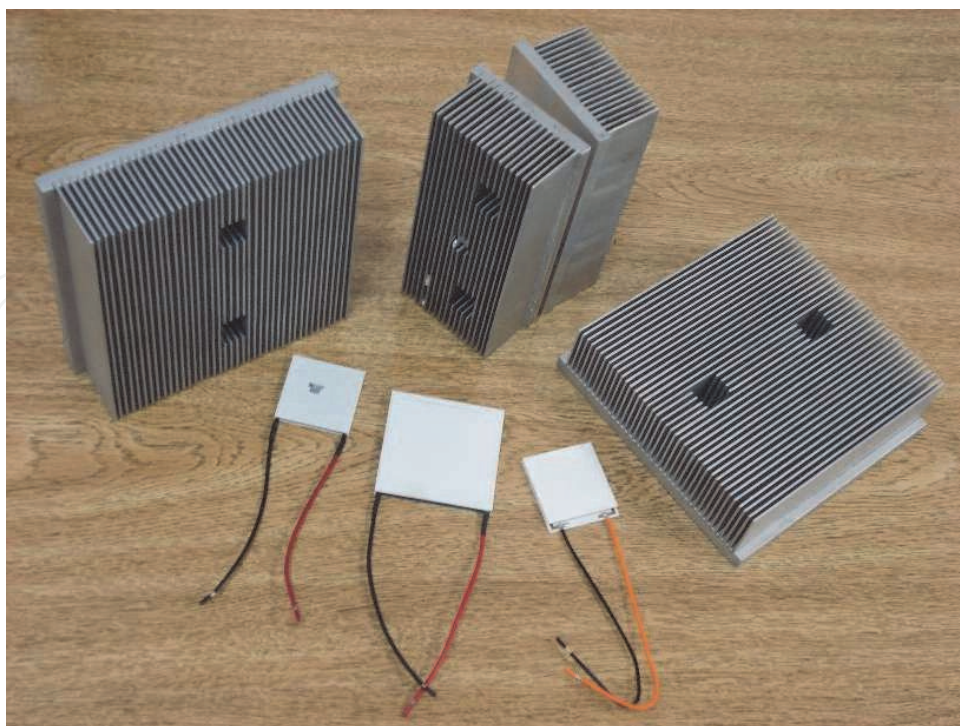


Fig. 1. Thermoelectric modules and heat sinks

Figure 1 shows thermoelectric modules and heat sinks commercially available.

A unique aspect of thermoelectric energy conversion is that the direction of energy flow is reversible. So, for instance, if the load resistor is removed and a DC power supply is substituted, the thermoelectric device can be used to draw heat from the “heat source” element and decrease its temperature. In this configuration, the reversed energy-conversion process of thermoelectric devices is invoked, using electrical power to pump heat and produce refrigeration. This reversibility distinguishes thermoelectric energy converters from many other conversion systems. Electrical input power can be directly converted to pumped thermal power for heating or refrigerating, or thermal input power can be converted directly to electrical power for lighting, operating electrical equipment, and other work. Any thermoelectric device can be applied in either mode of operation, though the design of a particular device is usually optimized for its specific purpose.

2. The Peltier and Seebeck effects

The name “thermoelectricity” indicates a relationship between thermal and electrical phenomena. The concepts of heat, temperature and thermal balance are among the most fundamental and important to the science. Two objects are considered to be in thermal equilibrium if the exchange of heat does not exist when they both are placed in contact. This is an experimental fact. Objects in the same temperature are said to be in thermal equilibrium. This is called zeroth law of thermodynamics.

Two objects at different temperatures placed in contact exchange energy in an attempt to establish thermal equilibrium. Any work done during this process is the difference of heat lost by an object and won by another object. This is the first law of thermodynamics, in other words, energy is always conserved.

The concepts of electric charge and electric potential are also essentials. Objects are composed of positive and negative charges. Opposite electric charges attract each other and equal charges repel. These are experimental facts. Objects are said to be in electric equilibrium if there is no heat exchange when they are placed in contact. Such objects are said to be at the same electrical potential. Objects with different electrical potential exchange charges in an attempt to achieve the same electrical potential.

The electric current is the amount of electric charges which pass through a boundary of a conductor per unit time and it is related to the variation of the electrical potential, in other words, the electrical gradient. Similarly, the heat flow is the amount of heat that passes through the boundary per unit of time. Likewise, the thermal flow is related to temperature variation, in other words, to the electrical gradient.

To understand the thermoelectric effect it is needed to visualize the phenomenon in a micro scale. In the nature, the materials are made of molecules composed by atoms. Depending on the kind of interlace between the atoms, the outer electrons are more or less likely of moving around the nucleus and other electrons.

In the purer metallic conductors outer electrons, less connected to others, can move freely around all the material, as if they do not belong to any atom. These electrons transmit energy one to another through temperature variation, and this energy intensity varies depending on the nature of the material.

For this reason, if two distinct materials are placed in contact, free electrons will be transferred from the more “loaded” material to the other, so they equate themselves, such transference creates a potential difference, called contact potential, since the result will be a

pole negatively charged by the received electrons and another positively charged by the loss of electrons.

The following sequence of metals shows, from left to right, which is more likely to lose electrons:

(+) Rb K Na Al Zn Pb Sn Sb Bi Fe Cu Ag Au Pt (-)

In the case of semi-conductors, the transference occurs because some of the atoms that compose it are already lacking some electrons. When voltage is applied, there is a tendency to drive electrons and complete the atomic orbit. When it occurs, the atomic conduction leaves "holes" that are essentially atoms with crystalline grids that now have positive local charge. The electrons are, then, continuously drawn out of the holes moving towards the next hole available. In fact, the embezzlement of these atoms is what drives the current.

Electrons move more easily in copper conductors than in semiconductors. When electrons leave the p element and entering the cold side of the copper, holes are created in the p type as the electrons go to a higher level of energy to reach an energy level of electrons that are already moving in the copper. The extra energy to create these holes come from the absorption of heat. Meanwhile, the newly-created holes move throughout the copper in the hot side. The hot side electrons of the copper move to the p element and complete the holes, releasing energy generated as heat.

The n-type conductor is doped with atoms which provide more electrons than the ones necessary to complete the atomic orbits within the crystalline grids. When the voltage is applied, these extra electrons move easily to the conduction band. However, additional energy is necessary so that the n-type electrons reach the next energy level of electrons arriving from the cold side of the copper. This extra energy comes from the heat absorbed. Finally, when the electrons leave the hot side of the n-type element, they can move freely again throughout the copper. They fall to a lower energy level, releasing heat in the process.

The information above do not cover all the details, but they can explain complex physical interactions. The main point is that the heat is always absorbed in the cold side of the elements p and n, and the heat is always released in the hot side of the thermoelectric element. The pumping capacity of the module heat is proportional to electric current and depends on the geometry of the element, the number of pairs and the properties of the material.

It is also possible to form a more conductive crystal by adding impurities with less valence electron. For instance, Indium impurities (which have 3 valence electrons) are used in combination with silicon and create a crystalline structure with holes. These holes make it easier to transport electrons throughout the material when the voltage applying a voltage. In this case, the holes are considered load conductors in this conductor "positively doped" which is referred as p-type.

3. Thermoelectric system configurations

3.1 Thermoelectric cooling device

The pairs of thermoelectric cooling are made of two semiconductors elements, frequently made of bismuth telluride highly doped to create an excess (n-type) or a deficiency of electrons (p-type). The heat absorbed at the cold junction is transferred to the hot junction at a rate proportional to the current passing through the circuit and the number of semiconductors pairs. In practice, pairs are combined into a module which they are electrically connected in series and thermally in parallel.

A thermoelectric device consists of several **n** and **p** pellets connected electrically in series and thermally in parallel sandwiched between two ceramic plates. When the thermoelectric module is operating as a refrigerator, the bottom plate is bonded to a heat sink and, with the application of DC current of proper polarity; heat is pumped from the top plate to the bottom plate and into the heat sink, where it is dissipated to ambient. The resultant is that the top surface becomes cold. The top surface can also supply heat by simply reversing DC polarity. The same unit can be converted into a thermoelectric power generator by simply replacing the DC source with the load, or item to receive power, and apply heat to the top surface of the thermoelectric modules. Electrical power is derived from the movement of electrical carriers brought on by heat flow through the thermoelectric pellets. Holes, or positive carriers, move to the heat sink side of the **p**-type pellet making that junction electrically positive. Similarly, electron flow in the **n**-type pellets results in a net negative charge at the heat sink side of the **n**-type pellet.

A heat sink is a device that is attached to the hot side of thermoelectric module. It is used to facilitate the transfer of heat from the hot side of the module to the ambient. A cold sink is attached to the cold side of the module. It is used to facilitate heat transfer from whatever is being cooled (liquid, gas, solid object) to the cold side of the module. The most common heat sink (or cold sink) is an aluminum plate that has fins attached to it. A fan is used to move ambient air through the heat sink to pick up heat from the module.

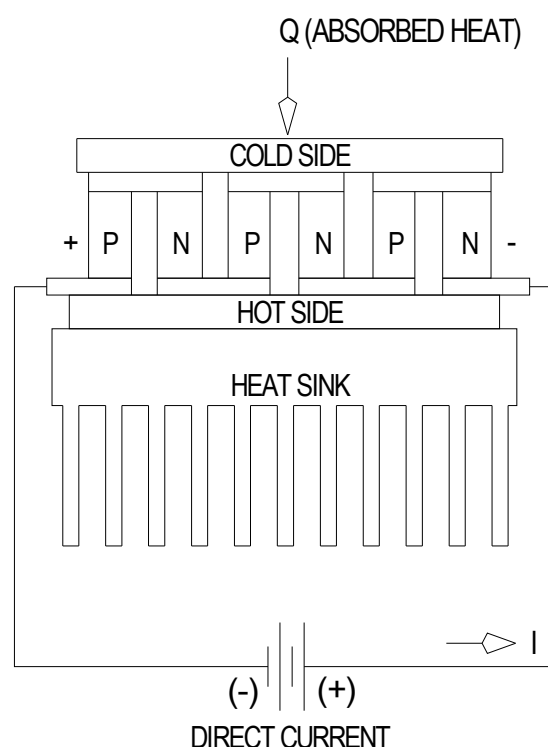


Fig. 2. Schematic of a Peltier effect (thermoelectric cooling device)

Figure 2 shows the configuration of a typical thermoelectric system that operates by the Peltier effect. The goal in this design is to collect heat from the volume of air and transfer it to an external heat exchanger and on to the external environment. It is usually done using two combinations of fan and heat sink together with one or more thermoelectric modules. The smallest sink is used together with the volume to be cooled, and cooled to a

temperature lower than the volume, so using a fan the heat that passes between the fins can be collected. In its typical configuration, the insert is installed between the hot and the cold side of the sink.

When a DC current passes through the module, it transfers heat from the cold side to the hot side. At the same time, the fan in the hot side will be circulating in the ambient air the heat transferred to the heat sink fins of the hot side. It is noteworthy that the heat dissipated in the hot side does not include only the heat transferred by the application, but also the heat generated inside the module ($V \times I$).

The heat sink transfers the heat like a steam cycle compressor system. For both, heating or cooling, it is necessary to use a sink to collect heat (heating mode) or dissipate heat (cooling mode) to the outside. Without it, the module is subject to overheating, with the hot side overheated the cold side also heats, consequently heat will not be transferred anymore. When the module reaches the temperature of reflow of the solder used, the unit will be destroyed. So a fan is always used as a heat sink to exchange heat with the external environment.

3.2 Thermoelectric power generator device

Figure 3 shows the configuration of a typical thermoelectric system that operates by the Seebeck effect.

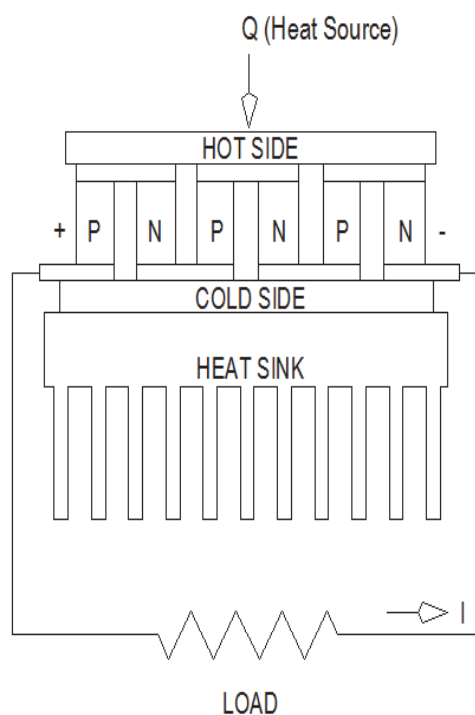


Fig. 3. Schematic of a thermoelectric power generator

There are some important practical considerations that should be made before attempting to use thermoelectric coolers in the power generation mode. Perhaps the most important consideration is the question of survivability of the module at the anticipated maximum temperature. Many standard thermoelectric cooling modules are fabricated with eutectic Bi/Sn solder which melts at approximately 138°C. However, there are some coolers being offered employing higher temperature solders designed to operate at temperatures of 200°C,

even approaching 300°C. In any case, consideration should be given to operational lifetime of a thermoelectric module exposed to high temperatures. Contaminants or even constituents of the solder can rapidly diffuse into the thermoelectric material at high temperatures and degrade performance and, in extreme cases, can cause catastrophic failure. This process can be controlled by the application of a diffusion barrier onto the TE material. However, some manufactures of thermoelectric coolers employ no barrier material at all between the solder and the TE material. Although application of a barrier material is generally standard on the high temperature thermoelectric cooling modules manufactured, they are mostly intended for only short-term survivability and may or may not provide adequate MTBF's (Mean Time Between Failures) at elevated temperatures. In summary, if one expects to operate a thermoelectric cooling module in the power generation mode, qualification testing should be done to assure long-term operation at the maximum expected operating temperature.

4. Mathematical modelling

4.1 Peltier effect

The parameters that are interesting to evaluate the performance of a cooling device are the coefficient of performance (ϕ), the heat pumping rate (Q_c) and the maximum temperature difference (ΔT_{\max}) that the device will produce.

The coefficient of performance (COP) ϕ is defined as

$$\phi = \frac{Q_c}{P} \quad (1)$$

where Q_c is the heat pumping rate from the cold side and P is the electrical power input. The "cooling effect" or "thermal load" is the heat pumping rate from the cold side and it is the sum of three terms: a) the Joule heat of each side per time unit, b) the heat transfer rate when current is equal to zero between the two sides and c) the Peltier heat rate of each side, that is, the heat removal rate is

$$Q_c = \alpha T_c I - \frac{1}{2} I^2 R - K \Delta T \quad (2)$$

where: $\alpha = (\alpha_p + \alpha_n)$ and α_p and α_n are properties of the semiconductors materials, I is the current, R is the electric resistance (Ω) and K is the total thermal conductance of the thermoelectric cooling module. The power input is

$$P = V \cdot I = \alpha \cdot I \cdot \Delta T + I^2 \cdot R = \frac{V(V - \alpha \cdot \Delta T)}{R} \quad (3)$$

where $\Delta T = (T_h - T_c)$ and T_h and T_c are the hot and cold sides temperatures. V is the applied voltage and is the sum of the electric and the Joule voltage.

$$V = \alpha \Delta T + IR \quad (4)$$

The coefficient of performance of the couple with this optimum geometry is:

$$\phi = \frac{\left[m T_c - \frac{1}{2} m^2 - \left(\frac{\Delta T}{Z} \right) \right]}{(m \Delta T + m^2)} \quad (5)$$

where Z is called the figure of merit of the thermoelectric association, defined by

$$Z = \frac{\alpha^2}{[(\rho_n K_n)^{1/2} + (\rho_p K_p)^{1/2}]^2} \quad (6)$$

where $m = \frac{IR}{\alpha}$

The coefficient of performance is strongly influenced by the figure of merit of the semiconductor material.

The current that maximizes the coefficient of performance is obtained by taking the derivative of the coefficient of performance with respect to m equal to zero and is

$$I_{ot} = \frac{\alpha \Delta T}{R(w-1)} \quad (7)$$

where

$$w = (1 + Z\bar{T})^{\frac{1}{2}} \quad (8)$$

The maximum coefficient of performance is given by

$$\phi_{\max} = \frac{T_c}{\Delta T} \left[\frac{w - \left(\frac{T_h}{T_c} \right)}{(w+1)} \right] \quad (9)$$

The resultant value of the applied voltage which maximizes the coefficient of performance is

$$V_{ot} = \frac{\alpha \Delta T w}{(w-1)} \quad (10)$$

The power input is given by

$$P_{ot} = \left(\frac{w}{R} \right) \left[\frac{\alpha \Delta T}{(w-1)} \right]^2 \quad (11)$$

The current that maximizes the heat pumping rate is given by

$$I_{ot} = \frac{\alpha T_c}{R} \quad (12)$$

Thus the maximum heat pumping rate at this current is calculated by

$$Q_{c \max} = \left(\frac{\alpha^2 T_c^2}{2R} \right) - K \Delta T \quad (13)$$

4.2 Seebeck effect

The important design parameters for a power generator device are the efficiency and the power output. The efficiency is defined as the ratio of the electrical power output. The efficiency is defined as the ratio of the electrical power output P_o to the thermal power input q_h to the hot junction

$$\eta = \frac{P_o}{q_h} \quad (14)$$

The power output is the power dissipated in the load. The thermal power input to the hot junction is given by

$$q_h = \alpha T_h I + \frac{1}{2} I^2 R + K \Delta T \quad (15)$$

where: α is the Seebeck coefficient, T_h is the hot side temperature of the thermoelectric module, I is the current, R is the electric resistance (Ω), K is the total thermal conductance of the thermoelectric cooling module and ΔT is temperature difference between hot and cold sides ($T_h - T_c$). In the discussion of power generators, the positive direction for the current is from the p parameter to the n arm at the cold junction. The electrical power output is

$$P_o = I^2 R_L = V I \quad (16)$$

where R_L is the load resistance. The current is given by

$$I = \frac{\alpha \Delta T}{(R + R_L)} \quad (17)$$

Since the open-circuit voltage is $\alpha \Delta T$. Thus the efficiency is

$$\eta = \frac{I^2 R_L}{\alpha T_h I + \frac{1}{2} I^2 R + K \Delta T} \quad (18)$$

The operating design, which maximizes the efficiency, will now be calculated. Let's take $S = R_L / R$. The efficiency is

$$\eta = \frac{\left(\frac{\Delta T}{T_h} \right) S}{\left\{ (1+S) - \left(\frac{\Delta T}{2T_h} \right) + \left[\frac{(1+S)^2 RK}{\alpha^2 T_h} \right] \right\}} \quad (19)$$

Again it is seen that the efficiency will be a maximum for RK minimized. Hence, the shape ratio, which maximizes the efficiency, is given by $\frac{\gamma_n}{\gamma_p} = \left(\frac{\rho_n k_p}{\rho_p k_n} \right)^{1/2}$. With this shape ratio the efficiency is

$$\eta = \frac{\left(\frac{\Delta T}{T_h}\right)s}{\left\{ (1+s) - \left(\frac{\Delta T}{2T_h}\right) + \left[\frac{(1+s)^2}{z T_h}\right] \right\}} \quad (20)$$

The optimum load is calculated by setting the derivative of the efficiency with respect to s equal to zero. The efficiency with both the geometric and load resistance optimized is

$$\eta = \frac{(\Delta T/T_h)(\omega+1)}{\left[\omega + (T_c/T_h)\right]} \quad (21)$$

Under optimum load, the output current is

$$I = \frac{\alpha \Delta T}{R(\omega+1)} \quad (22)$$

and the output voltage is

$$V = \frac{\alpha \Delta T \omega}{(\omega+1)} = \alpha (\Delta T) - I R \quad (23)$$

and the output power is

$$P_o = \left(\frac{\omega}{R}\right) \left[\frac{\alpha \Delta T}{(\omega+1)} \right] \quad (24)$$

The internal resistance R is the same as for a refrigerator and given by

$$R = \left(\frac{\alpha}{z^{1/2}}\right) \left(\frac{1}{\gamma_p}\right) \left(\frac{\rho_p}{k_p}\right)^{1/2} = \left(\frac{\alpha}{z^{1/2}}\right) \left(\frac{1}{\gamma_n}\right) \left(\frac{\rho_n}{k_n}\right)^{1/2} \quad (25)$$

or approximately by

$$R = (2L/A_T)(\rho_n + \rho_p) \quad (26)$$

In the previous equations, the load resistance and the shape ratio were adjusted to maximize the efficiency. In this section, these parameters will be selected to maximize the power output. The load resistance, which maximizes the power output, is obtained by setting equal to zero the derivative with respect to the load resistance of the power output given by Eqs. (18) and (19). The well-known result $R_L = R$ is obtained. With this load resistance, the output voltage is

$$V = \frac{1}{2} \alpha \Delta T \quad (27)$$

The current is

$$I = \frac{\alpha \Delta T}{2R} \quad (28)$$

and the power output is

$$P_o = \frac{(\alpha \Delta T)^2}{4R} \quad (29)$$

5. Selection and design

Selection of the proper thermoelectric module for a specific application requires an evaluation of the total system in which the cooler will be used. For most applications it should be possible to use one of the standard module configurations while in certain cases a special design may be needed to meet stringent electrical, mechanical, or other requirements. Although we encourage the use of a standard device whenever possible, Ferrotec America specializes in the development and manufacture of custom thermoelectric modules and we will be pleased to quote on unique devices that will exactly meet your requirements.

The overall cooling system is dynamic in nature and system performance is a function of several interrelated parameters. As a result, it usually is necessary to make a series of iterative calculations to "zero-in" on the correct operating parameters. If there is any uncertainty about which thermoelectric device would be most suitable for a particular application, we highly recommend that you contact our engineering staff for assistance.

Before starting the module selection process, the designer should be prepared to answer the following questions:

1. At what temperature must the cooled object be maintained?
2. How much heat must be removed from the cooled object?
3. Is thermal response time important? If yes, how quickly must the cooled object change temperature after DC power has been applied?
4. What is the expected ambient temperature? Will the ambient temperature change significantly during system operation?
5. What is the extraneous heat input (heat leak) to the object as a result of conduction, convection, and/or radiation?
6. How much space is available for the module and heat sink?
7. What power is available?
8. Does the temperature of the cooled object have to be controlled? If yes, to what precision?
9. What is the expected approximate temperature of the heat sink during operation? Is it possible that the heat sink temperature will change significantly due to ambient fluctuations, etc.?

Each application obviously will have its own set of requirements that likely will vary in level of importance. Based upon any critical requirements that cannot be altered, the designer's job will be to select compatible components and operating parameters that ultimately will form an efficient and reliable cooling system.

To the design of a thermoelectric system it is necessary to define the following parameters: temperature of cold surface (TC); temperature of hot surface (TH) and the amount of heat absorbed or removed by the cold surface of the thermoelectric module (QC).

If the object to be cooled is in deep contact with the cold surface of the thermoelectric module, the expected temperature of the object (TC) can be considered the temperature of the module's cold surface.

There are cases which the object to be cooled is not in deep contact with the cold side of the module, such as an amount of cooling which the heat exchanger in the cold surface of the thermoelectric module. When this kind of system is used, the cold surface required can be several degrees lower than the desired temperature of the object.

The hot surface temperature (TH) is defined by two important parameters:

1. The temperature of the environment which the heat is rejected.
2. The heat exchanger efficiency which is between the hot surface of TE and the environment.

These two temperatures TC and TH and the difference between them ΔT are very important parameters and, thus can be determined accurately if the project operated correctly.

The most difficult parameter to qualify is the amount of heat (QC) to be removed or absorbed from the cold surface of the thermoelectric module. All thermoelectric system thermal loads should be considered. These thermal loads include, but are not limited to a thermal load of the electronic device, I^2R and the conduction through any object in contact either with the cold surface or the hot surface (i.e. electrical conductors, air or gas around objects, mechanical fasteners, etc). In some cases the effects of the thermal radiation should also be considered.

Thermoelectric devices are capable of producing no-load temperature differential of 70°C. Higher temperature differentials can be achieved by cascading modules.

Once the three parameters are qualified, the selection process for a particular module starts. Basic equations of heat transfer as listed to quantify QC and T.

There are many sets of modules or group of modules that can be used in a specific application. An additional criterion frequently used to select the best module and the coefficient of performance (COP) that is defined as absorbed heat in the cold junction, divided by the total heat to be rejected by the heat exchanger.

The maximum COP has advantages of minimal power and thus minimal rejected heat by the exchanger. These advantages come at a cost which in this case is a thermoelectric device bigger to operate at a maximum COP. The major advantage of minimal COP is the lowest initial cost.

The power conversion efficiency is dependent on a variety of factors although typically it might end up at around 3%. The specific type of module that the designer needs to use is based on the heat sink, cold sink, heat flow, operating temperatures, and desired output. This requires an engineering analysis to tell exactly which module is best for each application.

Another thing to remember is that the designer will likely need power conditioning since the output power is directly related to the temperature difference. If the operating temperatures fluctuate at all, the power output will too. Generally, the system is designed such that maximum efficiency is achieved for the most common operating temperatures at the ideal voltage and current the designer require for each application.

6. Conclusion

Thermoelectric systems are solid-state heat devices that either convert heat directly into electricity or transform electric power into thermal power for heating or cooling. The

operation principles are the Seebeck and Peltier effects and the devices offer several advantages over other technologies.

Applications for thermoelectric modules cover a wide spectrum of product areas. These include equipment used by military, medical, industrial, consumer, scientific/laboratory, and telecommunications organizations. Each application will have its own set of requirements that likely will vary in level of importance. Nowadays the applications are restricted to small thermal systems but the trend in recent years has been for larger thermoelectric systems. So, the thermoelectricity is one important field for the development of environmentally friendly thermal systems and the researches of new thermoelectric materials with large Seebeck coefficient and appropriate technology could make a breakthrough in the applications of thermoelectric devices in many applications.

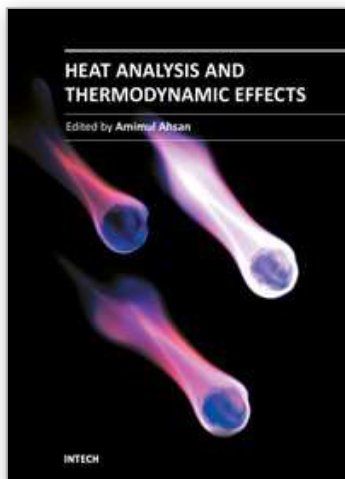
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The heat transfer and analysis on heat pipe and exchanger, and thermal stress are significant issues in a design of wide range of industrial processes and devices. This book includes 17 advanced and revised contributions, and it covers mainly (1) thermodynamic effects and thermal stress, (2) heat pipe and exchanger, (3) gas flow and oxidation, and (4) heat analysis. The first section introduces spontaneous heat flow, thermodynamic effect of groundwater, stress on vertical cylindrical vessel, transient temperature fields, principles of thermoelectric conversion, and transformer performances. The second section covers thermosyphon heat pipe, shell and tube heat exchangers, heat transfer in bundles of transversely-finned tubes, fired heaters for petroleum refineries, and heat exchangers of irreversible power cycles. The third section includes gas flow over a cylinder, gas-solid flow applications, oxidation exposure, effects of buoyancy, and application of energy and thermal performance index on energy efficiency. The fourth section presents integral transform and green function methods, micro capillary pumped loop, influence of polyisobutylene additions, synthesis of novel materials, and materials for electromagnetic launchers. The advanced ideas and information described here will be fruitful for the readers to find a sustainable solution in an industrialized society.

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