Review on Thermoelectric Devices

P. J. Patil¹, Prof. A. M. Patil²

¹PG student, ²Vice Principal, Department of Mechanical Engineering, PVPIT, Budhgaon, Sangali, India

Abstract— Thermoelectric devices is a solid-state active heat pump which transfers heat from one side of the device to the other side against the temperature gradient (from cold to hot), with consumption of electrical energy. Such an instrument is also called a Peltier device, Peltier heat pump, solid state refrigerator, or thermoelectric cooler (TEC). The main advantages of a Peltier cooler (compared to a vapor-compression refrigerator) are its lack of moving parts or circulating liquid, and its small size and flexible shape (form factor).

Keywords— Thermoelectric, Peltier Effect, Thermoelectric Material, Applications.

I. INTRODUCTION [1]-

The thermoelectric effect is the direct conversion of temperature differences to electric voltage and vice-versa. A thermoelectric device creates a voltage when there is a different temperature on each side. Conversely, when a voltage is applied to it, it creates a temperature difference. At the atomic scale, an applied temperature gradient causes charge carriers in the material to diffuse from the hot side to the cold side, similar to a classical gas that expands when heated; hence inducing a thermal current.

This effect can be used to generate electricity, measure temperature or change the temperature of objects. Because the direction of heating and cooling is determined by the polarity of the applied voltage, thermoelectric devices are efficient temperature controllers.

The term "thermoelectric effect" encompasses three separately identified effects: the Seebeck effect, Peltier effect and Thomson effect. Textbooks may refer to it as the Peltier–Seebeck effect. This separation derives from the independent discoveries of French physicist Jean Charles Athanase Peltier and Estonian-German physicist Thomas Johann Seebeck. Joule heating, the heat that is generated whenever a voltage is applied across a resistive material, is related though it is not generally termed a thermoelectric effect. The Peltier–Seebeck and Thomson effects are thermodynamically reversible whereas Joule heating is not.

II. THERMOELECTRIC COOLING

Thermoelectric cooling uses the Peltier effect to create a heat flux between the junctions of two different types of materials. A Peltier cooler, heater, or thermoelectric heat pump is a solid-state active heat pump which transfers heat from one side of the device to the other side against the temperature gradient (from cold to hot), with consumption of electrical energy. Such an instrument is also called a Peltier device, Peltier heat pump, solid state refrigerator, or thermoelectric cooler (TEC). The Peltier device is a heat pump: when direct current runs through it, heat is moved from one side to the other. Therefore it can be used either for heating or for cooling (refrigeration), although in practice the main application is cooling. It can also be used as a temperature controller that either heats or cools.

This technology is far less commonly applied to refrigeration than vapor-compression refrigeration is. The main advantages of a Peltier cooler (compared to a vapor-compression refrigerator) are its lack of moving parts or circulating liquid, and its small size and flexible shape (form factor). Its main disadvantage is that it cannot simultaneously have low cost and high power efficiency. Many researchers and companies are trying to develop Peltier coolers that are both cheap and efficient. (See Thermoelectric materials.)

A Peltier cooler is the opposite of a thermoelectric generator. In a Peltier cooler, electric power is used to generate a temperature difference between the two sides of the device, while in a thermoelectric generator, a temperature difference between the two sides is used to generate electric power. The operation of both is closely related (both are manifestations of the thermoelectric effect), and therefore the devices are generally constructed from similar materials using similar designs.

A. Peltier effect

The Peltier effect is the presence of heat at an electrified junction of two different metals and is named for French physicist Jean-Charles Peltier, who discovered it in 1834.
When a current is made to flow through a junction composed of materials A and B, heat is generated at the upper junction at $T_2$, and absorbed at the lower junction at $T_1$. The Peltier heat absorbed by the lower junction per unit time is equal to $Q = \Pi_{AB} I = (\Pi_B - \Pi_A) I$

Where $\Pi_{AB}$ is the Peltier coefficient for the thermocouple composed of materials A and B and $\Pi_A (\Pi_B)$ is the Peltier coefficient of material A (B). $\Pi$ varies with the material's temperature and its specific composition: p-type silicon typically has a positive Peltier coefficient below ~550 K, but n-type silicon is typically negative.

The Peltier coefficients represent how much heat current is carried per unit charge through a given material. Since charge current must be continuous across a junction, the associated heat flow will develop a discontinuity if $\Pi_A$ and $\Pi_B$ are different. Depending on the magnitude of the current, heat must accumulate or deplete at the junction due to a non-zero divergence there caused by the carriers attempting to return to the equilibrium that existed before the current was applied by transferring energy from one connector to another. Individual couples can be connected in series to enhance the effect. Thermoelectric heat pumps exploit this phenomenon, as do thermoelectric cooling devices found in refrigerators.

All electric current is accompanied by heat current (Joule heating). What Peltier observed was that when electric current passed across the junction of two dissimilar conductors (a “thermocouple”) there was a heating effect that could not be explained by Joule heating alone. In fact, depending on the direction of the current, the overall effect could be either heating or cooling. This effect can be harnessed to transfer heat, creating a heater or a cooler. Peltier himself did not appreciate the potential of his discovery, and it was not efficiently exploited until the end of the 20th century.

**B. How it Works**

When two conductors are placed in electric contact, electrons flow out of the one in which the electrons are less bound, into the one where the electrons are more bound. The reason for this is a difference in the so-called Fermi level between the two conductors. The Fermi level represents the demarcation in energy within the conduction band of a metal, between the energy levels occupied by electrons and those that are unoccupied.

When two conductors with different Fermi levels make contact, electrons flow from the conductor with the higher level, until the change in electrostatic potential brings the two Fermi levels to the same value. (This electrostatic potential is called the contact potential.). Current passing across the junction results in either a forward or reverse bias, resulting in a temperature gradient. If the temperature of the hotter junction (heat sink) is kept low by removing the generated heat, the temperature of the cold plate can be cooled by tens of degrees (Fig2).
TECs are constructed using two dissimilar semiconductors, one n-type and the other p-type (they must be different because they need to have different electron densities in order for the effect to work). The two semiconductors are positioned thermally in parallel and joined at one end by a conducting cooling plate (typically of copper or aluminium).

A voltage is applied to the free ends of two different conducting materials, resulting in a flow of electricity through the two semiconductors in series. The flow of DC current across the junction of the two semi-conductors creates a temperature difference. As a result of the temperature difference, Peltier cooling causes heat to be absorbed from the vicinity of the cooling plate, and to move to the other (heat sink) end of the device—see Fig2.

The heat is carried through the cooler by electron transport and released on the opposite ("hot") side as the electrons move from a high to low energy state.

When the two materials are connected to each other by an electrical conductor, a new equilibrium of free electrons is established. Potential migration creates an electrical field across each of the connections. When current is subsequently forced through the unit, the attempt to maintain the new equilibrium causes the electrons at one connection to absorb energy, while those at the other connection release energy.

In practice many TEC pairs (or couples), such as described above, are connected side-by-side, and sandwiched between two ceramic plates, in a single TEC unit. The heat pumping capacity of a cooler is proportional to the current and the number of pairs in the unit.
III. THERMOELECTRIC MODULE

Thermoelectric (TE) modules are small solid-state devices that function as heat pumps. A "typical" unit is a few millimeters thick by a few millimeters to a few centimeters square, as shown in below.

The ceramic material on both sides adds rigidity & necessary insulation. The electric conductors are usually made of copper and simply permit the flow of electrons. The cooling is proportional to the current and number of modules hence number of modules can be cascaded to achieve greater temperature difference.

In a thermo electric module the heat transferred to hot side is greater than that pumped by a quantity to joules heating (I²R loss) hence a good thermoelectric material must have low thermal conductivity to prevent heat loss through heat conduction between hot and cold sides and a high electrical conductivity to minimize joules heating. The best material for semiconductors so far developed is bismuth telluride that satisfies this condition.
TEC can achieve temperature differences up to 70°C, or can transfer heat at a rate of 125 W. To achieve greater temperature differences (up to 131°C), select a multistage (cascaded) modules. The use of thermoelectric modules often provides solutions, and in some cases the ONLY solution, to many difficult thermal management problems where a low to moderate amount of heat must be handled. While no one cooling method is ideal in all respects and the use of thermoelectric modules will not be suitable for every application.

A practical thermoelectric module generally consists of two or more elements of n and p-type doped semiconductor materials that are connected electrically in series and thermally in parallel. These thermoelectric elements and their electrical interconnects typically are mounted between two ceramic substrates. The substrates hold the overall structure together mechanically and electrically insulate the individual elements from one another and from external mounting surfaces. A typical unit is a few millimetres to few centimetres square. Most thermoelectric modules range in size from approximately 2.5-50 mm (0.1 to 2.0 inches) square and 2.5-5mm (0.1 to 0.2 inches) in height. A variety of different shapes, substrate materials, metallization patterns and mounting options are available.

The peltier effect has great advantages great advantages for the same purpose of load of the system.

Some of the more significant features of the thermoelectric modules are:

- No moving parts: - A thermoelectric module works electrically without any moving parts so they are virtually maintenance free.
- Small size and weight: - The overall thermoelectric cooling system is much smaller and lighter than a comparable mechanical system. In addition, a variety of standard and special sizes and configurations are available to meet strict application requirements.
- Ability to cool below ambient: - Unlike a conventional heat sink whose temperature necessarily must rise above ambient, a thermoelectric system attached to that same heat sink has the ability to reduce the temperature below the ambient value.
- Precise temperature control: - With an appropriate closed-loop temperature control circuit, thermoelectric module can control temperatures to better than +/-0.1°C.
- High Reliability: - Thermoelectric modules exhibit very high reliability due to their solid state construction. Although reliability is somewhat application dependent, the life of typical thermoelectric system is greater than 200,000 hours.
- Electrically Quite Operation: - unlike a mechanical refrigeration system, thermoelectric modules generate virtually no electric noise and can be used in conjunction with sensitive electronic sensors. They are also acoustically silent.
- Operation in any Orientation: - Thermoelectric modules can be used in any orientation and in zero gravity environments. Thus they are popular in many aerospace applications.
- Convenient Power Supply: - Thermoelectric modules operate directly from a DC power source.
- Spot Cooling: - With a thermoelectric module it is possible to cool one specific component or area only, thereby often making it necessary to cool an entire package or enclosure.
- Ability to Generate Electric Power: - When used ‘in reverse’ by applying a temperature differential across the faces of a thermoelectric refrigeration system, it is responsible to generate a small amount of DC power.
- Environmental Friendly: - Conventional refrigeration system cannot be fabricated without using chlorofluorocarbons or other chemicals that may be harmful to environment. Thermoelectric devices do not use or generate gases of any kind.
- Another benefit to thermoelectric devices is that they convert thermal energy directly into electricity, or vice-versa. Direct conversion eliminates losses associated with multiple energy conversion processes. Direct conversion also means there is no need for additional equipment or materials, making for a simplified device. Thermoelectric energy conversion is done in the solid state. As such, the devices have no moving parts that can wear out.

IV. THERMOELECTRIC MATERIALS

Thermoelectric materials take advantage of the coupling between thermal and electrical currents, and are used for the direct conversion between thermal and electrical energy. With these materials, electricity can be used to pump heat (thermoelectric coolers) or waste heat can be used to generate electricity (thermoelectric generators).
Thermoelectric coolers are designed to utilize the Peltier effect described above. These types of coolers have no moving parts and as a result are quiet and require little maintenance. Because of these advantages, they are useful in a wide variety of niche applications: cooling laser diodes and computer electronics, providing air conditioning in submarines, powering space probes, and even to chill food and drinks in portable picnic coolers (powered by car batteries). Unfortunately, the best materials used in Peltier coolers today cannot compete with the efficiencies of traditional cooling devices, such as the compressor in a household refrigerator.

Therefore, the primary objective of our research is to find new materials which could be used to make more efficient thermoelectric coolers. If more efficient devices could be made, there would be a number of new and exciting applications for Peltier coolers.

The Peltier junction mentioned above consists of two materials, one with a positive thermopower and one with a negative thermopower. Since the charge carriers in p-type materials and n-type materials have opposite sign, their thermopowers have opposite sign.

Schematic of a TE device. Since the charge carriers move in a different direction in each leg, each carries heat away from the cold end. It is more than just the thermopower that determines the performance of a device.

We need the electrical resistivity to be small so energy is not wasted in Joule heating. We also need the thermal conductivity to be small so heat we pump to the hot end stays there. For maximum device efficiency, we need to maximize each material's dimensionless Figure of Merit (ZT).

\[
ZT = \frac{T S^2}{\rho \kappa}
\]

Where:
- \(S\) = thermopower (V/K)
- \(\rho\) = electrical resistivity (\(\Omega\)cm)
- \(\kappa\) = thermal conductivity (W/cmK)
- \(T\) = temperature (K)

At present, the best materials are small band gap semiconductors; optimized Bi\(_2\)Te\(_3\) has \(S = 220\ \mu\text{V/K}\) and \(ZT \approx 1\) at room temperature.

However, a \(ZT\) greater than 3 is needed to compete with traditional cooling technologies. Our goal is to find new materials with \(ZT > 1\) at or below room temperature [6].
A. Applications of thermoelectric devices as Power generation

A thermoelectric power generator is a solid state device that provides direct energy conversion from thermal energy (heat) due to a temperature gradient into electrical energy based on “Seebeck effect”. The thermoelectric power cycle, with charge carriers (electrons) serving as the working fluid. The major drawback of thermoelectric power generator is their relatively low conversion efficiency (typically ~5%). This has been a major cause in restricting their use in electrical power generation to specialized fields with extensive applications where reliability is a major consideration and cost is not. Applications over the past decade included industrial instruments, military, medical and aerospace and applications for portable or remote power generation.

B. Solar thermoelectric generation

The growing demand for energy throughout the world has caused great importance to be attached to the exploration of new sources of energy. Among the unconventional sources, solar energy is one of the most promising energy resources on earth and in space, because it is clean and inexhaustible. Applications of solar thermoelectric generator are attractive. The use of the sola thermoelectric generator usually combines a solar thermal collector with a thermoelectric generator, which delivers the electric energy.

Thermoelectric power generation is based on a phenomenon called “Seebeck effect” discovered by Thomas Seebeck in 1821. When a temperature difference is established between the hot and cold junctions of two dissimilar materials (metals or semiconductors) a voltage is generated, i.e., Seebeck voltage. A schematic diagram of a simple thermoelectric power generator operating based on Seebeck effect is shown in Fig. (6). As shown in Fig. (6), heat is transferred at a rate of $Q_H$ from a high-temperature heat source maintained at $T_H$ to the hot junction, and it is ejected at a rate of $Q_L$ to a low-temperature sink maintained at $T_L$ from the cold junction. Based on Seebeck effect, the heat supplied at the hot junction causes an electric current to flow in the circuit and electrical power is produced. Using the first-law of thermodynamics (energy conservation principle) the difference between $Q_H$ and $Q_L$ is the electrical power output $W_e$. It should be noted that this power cycle intimately resembles the power cycle of a heat engine (Carnot engine), thus in this respect a thermoelectric power generator can be considered as a unique heat engine.

![Fig.6 Schematic diagram showing the basic concept of a simple thermoelectric power generator operating based on Seebeck effect.](image-url)
C. Application of thermoelectric devices as cooler-

Thermoelectric cooling is a form of solid-state refrigeration; it has the advantage of being compact and durable. A thermoelectric cooler uses no moving parts (except for some fans), and employs no fluids, eliminating the need for bulky piping and mechanical compressors used in vapor-cycle cooling systems. Such sturdiness allows thermoelectric cooling to be used where conventional refrigeration would fail. Thermoelectric devices also have the advantage of being able to maintain a much narrower temperature range than conventional refrigeration. They can maintain a target temperature to within ±1°C or better, while conventional refrigeration varies over several degrees.

Unfortunately, modules tend to be expensive, limiting their use in applications that call for more than 1 kWh of cooling power. Owing to their small size, if nothing else, there are also limits to the maximum temperature differential that can be achieved between one side of a thermoelectric module and the other. However, in applications requiring a higher ΔT, modules can be cascaded by stacking one module on top of another. When one module’s cold side is another’s hot side, some unusually cold temperatures can be achieved [1].

D. For medical application-

Thermoelectric cooling is widely used in many areas of science and technology, in particular, in medicine. It is well known in medical practice that temperature effects are an important factor in treatment of many diseases of the human organism. To achieve low temperatures, systems with liquid nitrogen are used, which limits their use in hospitals significantly. In most cases such devices are bulky, without proper temperature control and thermal modes reproduction. Therefore, the use of thermal effects on the patient is confronted with some difficulties and is reduced mainly to the application of ice or hot water. The use of thermoelectric cooling can solve this problem, because it has several advantages, if compared to conventional techniques of thermal effects. Fundamental research on the application of thermoelectric cooling in medicine confirms the possibility of its practical application in such areas of medicine as cryotherapy, cryosurgery, ophthalmology, traumatology, neurosurgery, plastic surgery, gynecology, urology, oncology, dermatology etc [5].

In dermatology thermoelectric devices are used for cryomassage procedures (stimulation of metabolism, smoothing of wrinkles) for the treatment of pyoinflammatory processes, freezing out warts, hardening of individual parts of human body and other medical procedures. Therefore, the development and improvement of thermoelectric medical devices for skin diseases treatment is of current importance.

VI. CONCLUSIONS

1. Thermoelectric technology has been used practically in wide areas recently. The thermoelectric devices can act as coolers, power generators, or thermal energy sensors and are used in almost all the fields such as military, aerospace, instrument, biology, medicine and industrial or commercial products.

2. Still thermoelectricity not used more widely because the coupling between the electrical and heat currents is weak in most materials, and the overall energy conversion efficiency is therefore very low. Therefore, researchers are working hard to discover new p- and n-type semiconductors, which can do this more efficiently.

REFERENCES


