IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

Thermoelectric Cooling: A Review Of The Peltier Effect As An Alternative To Conventional Refrigeration

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Abstract: This review paper explores the principles, materials, and applications of the Peltier effect as an alternative to traditional refrigeration systems. Conventional vapor compression refrigeration, while effective, faces significant challenges including environmental harm from refrigerants, noise pollution, high energy consumption, and operational costs. The Peltier effect, a thermoelectric phenomenon where heat is absorbed or released at the junction of two different conductors or semiconductors under electric current, offers a solid-state solution for cooling and heating without moving parts. The paper details the microscopic mechanism of the Peltier effect, its relationship with the Seebeck effect, and the key equations governing thermoelectric junctions. The figure of merit (ZT) is discussed as a critical parameter for evaluating thermoelectric materials, with bismuth telluride (Bi2Te3) highlighted as the most widely used material for room-temperature applications. The construction of Peltier modules, their advantages—such as silent operation and reliability—and disadvantages, including lower efficiency and higher cost compared to traditional systems, are analyzed. The review concludes that while current Peltier modules have limitations, ongoing material advancements hold promise for more efficient and environmentally friendly refrigeration technologies in the future.

Index Terms **-** Peltier effect, thermoelectric, sustainability, refrigeration, cooling.

Traditional Refrigeration System:

Humans have used many methods for cooling from ancient times. The cooling is primarily used for storing food for longer periods, to get different food delicacies or to have better room temperature. The modern society uses refrigerators, water coolers, air-conditioners etc. to get the same effect. Vapour compression refrigeration is one of the most common methods for cooling food in residential and commercial places. The main components of a vapour compression system are the compressor, condenser, evaporator, and expansion valve (also called a throttle valve). The refrigerant moves through the components above and undergoes a phase change, resulting in heat absorption and rejection.

The system is, as such, useful. However, there are many problems with the system. First and foremost is the refrigerant itself. There are various refrigerants used depending on the application. The traditional refrigerant used earlier for residential purposes was R12 or R22. Both gases were found to affect the ozone layer of the Earth. Other refrigerants are also found to have high global warming potential, which raises sustainability concerns.

Apart from global warming concerns, the traditional refrigeration systems are noisy due to the presence of moving components and especially the compressor. They need high electricity power to run. The operation costs of these systems are also high. The air-conditioning systems working of vapour compression cycle require extensive ductwork and many times civil rework at homes.

Alternative Refrigeration System:

The main purpose of a refrigeration system is to extract heat from the source at a lower temperature and transfer that heat to a sink at a higher temperature. The second law of thermodynamics clearly explains that it is impossible to do this without doing some external work. Vapour compression system as well as vapour absorption system work on the same law.

Another alternative method for extracting heat is using thermoelectric systems. A thermoelectric system is a solid-state device that converts heat into electricity or vice versa using the thermoelectric effect. The thermoelectric effects like Seeback and Peltier are primarily used by the thermoelectric systems.

Seebeck effect is a thermoelectric phenomenon in which a voltage is generated across two different conductors or semiconductors when there is a difference in temperature between their junctions. This effect is primarily used in thermoelectric generators for producing electricity.

The Peltier effect is a thermoelectric phenomenon in which heat is absorbed or released at the junction of two different conductors or semiconductors when an electric current flows through them. If current flows one way, the junction absorbs the heat i.e. cooling effect is observed. If the current reverses, the junction releases heat, i.e. heating effect is observed. This forms the basis for solid-state refrigeration in thermoelectric coolers.

The next sections explain how the Peltier effect can be used for solid-state refrigeration.

Peltier Effect at Microscopic Level:

Electric current is the flow of electrons. This is called a charge. So one can say the electrons are the charge carriers. The charge carriers carry not only charge but also energy. The level of energy of electrons is called Fermi level. When the carrier crosses from one material to another with a different Fermi level, its average energy changes. That change is either transferred to or taken from the lattice at the junction as heat. If carriers lose energy on crossing the junction, heat is released into the lattice and thus the junction is heated. If carriers gain energy, heat is absorbed and thus the junction is cooled. Thus the Peltier heating/ cooling is an interfacial energy associated with the materials' electronic properties.

Relation Between Seebeck Effect and Peltier Effect:

Seebeck effect is the generation of an electromotive force when the temperature difference is applied across two dissimilar conductors or semiconductors. The Seebeck coefficient quantifies this behaviour as given below:

$$S = \frac{V}{\Delta T}$$

Where,
V = Voltage generated
ΔT = Temperature difference

The sign of S indicates the dominant charge carrier: positive for holes (p-types) and negative for electrons (n-type).

Peltier effect is inverse of the Seebeck effect. When an electric current passes through the junction of two different materials, heat is either absorbed or released at the junction depending on the direction of current flow. This effect enables active cooling or heating without mechanical components. The Peltier coefficient Π represents the amount of heat carried per unit electric current and is given by:

$$\Pi = \frac{Q}{I}$$

Where,
Q = Heat absorbed or released
I = current

The relationship between Seebeck Effect and Peltier Effect is given by the following equation:

$$\Pi = ST$$

Where,
Π = Peltier Coefficient measured in V.K unit
S = Seebeck Coefficient measured in V/K
T = Absolute temperature in Kelvin

A higher Π implies greater heat pumping capability.

Key Equations for a Thermoelectric Junction:

Let us consider the thermoelectric junction. Let us consider that current I is flowing through it. The temperature difference is $\Delta T = T_{hot} - T_{cold}$.

The heat flow at hot junction will be

$$\dot{Q}_P = \Pi I$$

The heat flow at cold junction will be

$$\dot{Q}_c = \Pi_c I - \frac{1}{2} I^2 R - K\Delta T$$

Where,

- Π_c is the Peltier coefficient at the cold junction
- R is the electrical resistance of the leg. $\frac{1}{2} I^2 R$ indicates Joule heating and is shared by both hot and cold sides.
- K is the thermal conductance of the junction. $K\Delta T$ indicates the heat leaking from hot to cold by conduction

Thus, this equation shows three competing effects:

1. Peltier cooling indicated by the first term
2. Joule heating indicated by the third term and
3. Heat conduction back from the hot to the cold junction is indicated by the third term

Both the second and the third terms are detrimental.

The electrical power input needed for thermoelectric device is given by:

$$P = \Pi_h I + I^2 R + K\Delta T$$

Figure of Merit and Efficiency:

Figure of Merit written as Z or ZT tells how good a material is for thermoelectric applications. It combines Seebeck effect, electrical conductivity, and thermal conductivity into one performance indicator. Figure of merit tells how efficiently a material can convert heat into electricity or vice-versa. High ZT means the material can convert a big voltage from a temperature difference and is a poor thermal conductor.

For Peltier cooling, high ZT means:

- Larger possible temperature difference
- Better cooling performance
- Higher coefficient of performance (COP)

For thermoelectric material,

$$Z = \frac{S^2 \sigma}{k}$$

And the dimensionless figure of merit

$$ZT = \frac{S^2 \sigma T}{k}$$

Where,

S is the Seebeck coefficient (V/K). For high ZT, it is desirable to have a higher value of S.

σ is electrical conductivity (1/Ω.m). For high ZT, it is desirable to have a higher value of σ.

k is thermal conductivity (W/m-K). For high ZT, it is desirable to have a lower value of k.

T is absolute temperature (K).

The thermoelectric coolers usually have ZT ~ 1. This limits the maximum ΔT to roughly 60-70°C. Higher ZT will allow better cooling. This will also allow for a larger difference in the semiconductor temperatures. This will also lead to lower power consumption.

The material used for building Peltier modules is usually bismuth telluride (Bi_2Te_3). The value of ZT for bismuth telluride is between 0.8 to 1.0.

Common Materials Used for Peltier Modules:

Various materials have been used for developing Peltier modules. They are discussed below:

(a) Bismuth Telluride (Bi_2Te_3)

a. It is the most widely used thermoelectric material for applications working at the room temperature.
b. It is available in both p-form and n-form.
c. It meets the important criteria of having higher Seebeck effect and lower thermal conductivity.

   d. It has been successfully used in thermoelectric coolers for electronics, medical devices and portable coolers.

(b) Antimony Telluride (Sb_2Te_3)
   a. It is often used along with bismuth telluride to form p-type legs in thermoelectric modules
   b. It helps in enhancing the performance of thermoelectric module in the temperature range of 200-300 K.

(c) Lead Telluride (PbTe)
   a. It is suitable for the applications which are in the temperature range of 400-600 K
   b. It is used in the power generation and aerospace domains

(d) Silicon Germanium Alloys (SiGe):
   a. It is effective in the temperature range greater than 700 K.

(e) Skutterudites
   a. They are complex compounds based on cobalt.
   b. They have good thermoelectric performance at relatively high temperatures

Module Construction:

For creating Peltier modules, p-n thermoelectric legs are connected such that from an electrical perspective, they are in series and from a thermal perspective, they are in parallel. They are then put between ceramic plates that serve the following functions:

- Serve as insulating structural plates
- Provide mechanical support
- Help in thermal spreading

Advantages:

- No moving parts
- Silent operation
- High reliability
- Fine temperature control
- Same module can be used for heating and cooling

Disadvantages:

- Low efficiency (COP) than traditional refrigeration
- Relatively high cost per watt of cooling
- It is very important to remove heat from the module for effective use of the module

Conclusion:

Traditional refrigeration systems have been used for quite some time. There have been many problems with the system. Refrigerants are affecting the environment. There is a problem with noise pollution caused by the moving parts. There is an alternative possibility of using thermoelectric modules to get a refrigerating effect. They do not have any moving parts. They are reliable and are silent in operation. Additionally, they do not impact the environment. Right now, they have a low coefficient of performance in comparison to the traditional system. However, the future development of better materials can help in solving the problem and increase the coefficient of performance.

References:

[1] Mahmood, Hind Abdulrahman, Ameer Abed Jaddoa, and Mohammed K. Al-Saadi. "Improving the Performance of Thermoelectric Systems for Air Conditioning Using Different Configurations." (2025).

[2] Song, Kaidong, et al. "New Directions for Thermoelectrics: A Roadmap from High-Throughput Materials Discovery to Advanced Device Manufacturing." Small Science 5.3 (2025): 2300359.

[3] Xu, Qian, et al. "Small, affordable, ultra-low-temperature vapor-compression and thermoelectric hybrid freezer for clinical applications." Cell Reports Physical Science 4.12 (2023).

[4] Elsheikh, Mohamed Hamid, et al. "A review on thermoelectric renewable energy: Principle parameters that affect their performance." Renewable and sustainable energy reviews 30 (2014): 337-355.

[5] Nikam, Ajitkumar N., and Jitendra A. Hole. "A Review on use of Peltier Effects." International Journal of Science, Spirituality, Business And Technology (IJSSBT) 2.2 (2014).

[6] Tsutsui, Makusu, et al. "Peltier cooling for thermal management in nanofluidic devices." Device 2.1 (2024).

[7] Qian, Sheng, Chenguang Fu, and Tiejun Zhu. "Thermoelectric cooling goes cooler." National Science Open 4.3 (2025): 20250009.

[8] Yusop, Azdiana Md, et al. "Cooling the future: Peltier thermoelectric solutions for photovoltaic panels." International Journal of Ambient Energy 45.1 (2024): 2372361.

[9] Khan, Yousaf, et al. "Experimental Investigation of Peltier Based Thermoelectric Cooling System for Vaccine Storage." Journal of Computing & Biomedical Informatics 6.02 (2024): 139-147.

[10] Dumitru, George, et al. "Cooling System and Temperature Control of an Enclosure using Peltier Modules." Electrotehnica, Electronica, Automatica 72.1 (2024).

[11] Sujono, Sujono, and Hernawan Novianto. "Experimental study on the performance of Peltier TEC12706 as a cooling and heating media." Jurnal Polimesin 22.6 (2024): 600-604.