Thermoelectric Cooling Technology
Will Peltier modules supersede the compressor?
Peltier elements are thermoelectric components that can pump heat from one side of the device to the other depending on the direction of current. Although the principle has long been known, only state-of-the-art semiconductor materials enabled the breakthrough of Peltier technology. The strengths of Peltier technology lie in the scalability of the cooling elements, their location independence, reliability and precision control. In addition, Peltier elements have no moving parts, essentially making them vibration- and noise-free. The primary advantage over conventional compressor cooling units is elimination of flammable or environmentally harmful refrigerants. However, maximum performance and efficiency of Peltier cooling systems are considerably lower than that of compressor systems. Significantly higher energy costs for standard refrigerators and freezers should be expected and greater heat dissipation accepted.

With its particular characteristics, Peltier technology is opportune for a broad spectrum of special applications, but will not replace compressors for applications such as household refrigerators due to its inefficiency.
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Thermoelectric effects

History

The Seebeck effect
In 1821, Baltic German physicist Thomas Johann Seebeck (1770 – 1831) discovered that a compass needle was deflected by a closed loop formed by two metals joined in two places, with a temperature difference between the junctions. At the same time, Danish physicist Hans Christian Ørsted was studying the phenomenon of electromagnetism and correctly interpreted Seebeck’s “thermoelectric” effect, namely a difference in temperature caused by current flow, which in turn causes the magnetic field observed by Seebeck.

The Peltier effect
Only thirteen years after the discovery of the thermoelectric effect, French physicist Jean Charles Athanase Peltier (1785 – 1845) observed the reverse effect, the formation of a difference in temperature at the contact points of two different electrical conductors with the flow of an electric current.

At the time, Peltier could not correctly explain the effect, which Irish British physicist William Thomson (also known as Lord Kelvin, namesake of the SI unit of temperature) subsequently provided with his theory of thermoelectric currents in 1860.
Thermoelectric effects
Physical background

Thermoelectric power
The thermoelectric effects essentially involve various phenomena linked by a common material constant. The so-called thermoelectric power $Q$ differs for metallic conductors only by a few $\mu$V/K. However, for technical implementation of the Peltier effect, a pair of electrical conductors having a much higher thermoelectric voltage is required. To this point, it has been found only certain semiconductors satisfy this condition at room temperature.

The Peltier coefficient $\Pi$ is the product of thermoelectric power and temperature (Kelvin Relation):
$$\Pi = Q \cdot T$$

The Peltier (W) heat released at the interface between two conductors is
$$W = (\Pi_A - \Pi_B) \cdot I$$

The heat transfer depends on the difference of the Peltier coefficients and is proportional to current flow $I$. The sign of the heat flow depends on the current direction. A negative sign denotes heat absorption at the contact point.

However, electrical loss grows faster with increasing current than heat transfer through the Peltier effect. Consequently, cooling capacity no longer increases from a certain current intensity despite the increase in the current and even decreases.

Thermoelectric cooling
The Peltier effect can technically be used for cooling. The side to be cooled with temperature $T_0$ stands opposite to a heat reservoir of temperature $T_1$.

$$(T_0 - T_1)_{\text{max}} = \frac{1}{8} \cdot (\Pi_A - \Pi_B) \cdot \frac{\sigma}{\lambda}$$

The maximum achievable temperature difference is proportional to the electrical conductivity $\sigma$ and inversely proportional to the thermal conductivity $\lambda$, i.e. two opposing properties.

Apart from the required thermoelectric voltage, this is exactly what constitutes the second challenge for technical implementation of the Peltier effect, as most good electrical conductors also conduct heat very well.
Technical implementation of thermoelectric cooling
Design of a Peltier element

Thermocouple
The smallest component of a thermal element is the thermocouple. It consists of two electrical conductors with very different Seebeck coefficients to generate the highest possible thermoelectric voltage. The material used is most often semiconductor blocks connected at the ends with a copper. Up to now, the material most suitable for ambient temperature applications has been bismuth telluride in n- and p-doping.

Thermal element
A state-of-the-art Peltier element consists of a multitude of thermocouples connected electrically in series by copper bridges. The cooper bridges on each side are thermally bonded together by ceramic plates (usually aluminum oxide), but electrically isolated from each other. Even when p- and n-doped semiconductor material is used, the discussion is not about semiconductor technology in the proper sense such as in semiconductor diodes. There, the two semiconductors must be in direct contact to inhibit the current flow in one direction. In the Peltier element on the other hand, this is not helpful and the various semiconductors are usually connected by metal bridges. Semiconductors are therefore only preferred over other conductor materials because materials with high thermoelectric voltage have been found in this material group that conduct electricity very well, but are thermally isolating. Only then can the cold side be effectively separated from the warm and produce a usable temperature difference.
A Peltier module consists of one or more Peltier elements and thermally coupled heat sinks. The electric power used to pump is irreversibly converted into heat in the Peltier elements and must be dissipated effectively. Furthermore, the Peltier elements reversibly pump heat from one side to the other depending on the direction of the current. Consequently, heat is absorbed on one side, but which is significantly less than that emitted on the other side. Accordingly, heat must be exchanged across large-sized heat sinks, which lie on both sides of the Peltier element in a heat transmitting manner. Powerful fans usually divert the heated or cooled air.
Technical implementation of thermoelectric cooling

Controlling a Peltier system

Peltier elements are often controlled by pulse width modulation wherein the average current is controlled by the length of current pulses of high frequency. Voltage regulation is also a common method. However, simple on-off control is hardly used because of the heavy load on the Peltier element, shortening the service life of the element significantly.

Thermal stress
Even if it is possible to regulate Peltier modules by simply reversing the polarity, one should still be clear about the consequences. When reversing the direction of the current before the temperature in the Peltier element has equalized, the component is exposed to enormous thermal stress. Manufacturers of Peltier chips test the cycle stability of their products by reversing polarity directly provoking failure after just a few hundred cycles. Certain modifications can increase cycle stability.

In scientific fields, where the long-term stability and reliability of the units matters most, a shorter service life is normally unacceptable.
Comparison of cooling technologies

The strengths of Peltier systems
In general, Peltier elements are very reliable, low maintenance and durable due to the absence of moving parts subject to wear. In addition, they operate quietly and vibration-free. They can be small and lightweight even when combining several modules in one element. Another advantage is low-cost manufacturing. Peltier systems contain no refrigerants that are flammable, ozone depleting or that contribute to the greenhouse effect. The entire cooling system with compressor, inductor and large evaporator and condenser components is eliminated. Peltier elements are maintenance-free and quick and easy to replace in case of failure.

State-of-the-art control technology makes it possible to more accurately meter the cooling effect than for conventional compressors. It is also possible to reverse the function of the system by reversing the polarity, i.e. a cooling element can be turned into an efficient heating element.

The weaknesses of Peltier systems
With Peltier modules, there is no way technically to get around that fact that the hot and cold sides are very close together. In practice, today’s Peltier modules are only 3 to 5 mm thick. This fact makes it particularly important to efficiently carry the heat to and from the module. Technically, this is handled by large heat sinks with fans.

The performance of a Peltier module is directly related to the required temperature difference. The greater this difference in temperature, the lower the pumping capacity until it (based on the present state of Peltier technology) comes to a complete standstill at approx. 70 K. Greater temperature differences can only be accomplished by complex multistage elements.
Comparison of cooling technologies

The energy efficiency
Peltier elements can absorb heat on one side and dissipate heat on the other. The medium used for this reversible pumping process is the electric current or its charge carriers. The current acts to some extent as refrigerant in the cooling cycle and the pumping capacity is proportional to the current flow. It is unpreventable that this current is irreversibly converted into Joulean heat in the Peltier element with its property as ohmic resistor. The generation of heat not only means a loss of power, but in addition, the resulting loss of heat on the cold side must be compensated for by the pumping capacity before a net cooling capacity results.

In practice, a multiple of heat pumping capacity must be accepted as loss of power for Peltier systems. The cooling capacity of compressor systems, in contrast, exceeds the work to be invested by approx. two-fold.
Thermoelectric cooling technology is used wherever compressors are not suitable because of their size, if energy efficiency plays a secondary role or only low level cooling is required.

Household and leisure
For active cooling of food and beverages, Peltier-based coolers are very suitable for cars or campers because they are portable and can be connected to the 12 V electrical system directly.
A fundamental disadvantage of the Peltier modules is used in dehumidifiers. The air to be dehumidified is fed from the cold side of the Peltier module and the resulting condensation is collected in a pan.

Science
A well-known example of Peltier temperature control is the thermocycler, a laboratory device for multiplying DNA sequences. For this so-called PCR (polymerase chain reaction), three different reaction temperatures are required in rapid succession.
Compressor systems cannot be scaled. In contrast, Peltier modules can be extremely small with astonishing cooling capacity. Such miniature Peltier elements are used, for example, in scintillators where the noise of the photodiodes must be reduced by cooling.
Operation of conventional compressor systems depends on the position. When tilted or even on its head, compressor systems quit their service as in weightlessness. In contrast, Peltier modules can be used to build mobile devices operated by a readily available 12 V battery. Example: Density meters, viscometers, rheometers or refractometers.
Areas of application of Peltier technology

Special applications
Peltier elements give off more heat than they can pump. For standard computer processes, therefore, advanced heat sink and heat transfer elements have prevailed that only need to dissipate the heat generated by the processor. Only when processor temperatures less than ambient temperature are required is Peltier technology used.

Multistage Peltier modules can generate a temperature difference of more than 100 k and are used, for example, for IR sensors or dew point mirror hygrometers. Diffusion cloud chambers used to detect various particles (alpha radiation, electrons, positrons) require both cooling and heating. Peltier technology is ideally suited in such cases.

Cooled incubators
Only recently Peltier technology has found its way into the cooled incubators of the laboratory world. To provide consistently low temperatures (e.g. below 10 °C), they are less suitable. However, for incubation at or around room temperature (15 – 30 °C) or for applications with heat input, such units can be operated economically.

In such cases, poor energy efficiency is of little consequence as cooling runs at a low level without demanding maximum power. Average power consumption can fall below that of a conventional cooled incubator and the technical complexity of a compressor system with its disadvantages can be eliminated.
Conclusions

Peltier technology opens new opportunities for special applications, especially if it does not require maximum cooling power or energy efficiency. Its scalability and location independence enable the development of small or portable units. Peltier modules make temperature control efficient at lower temperature gradients by fine metering of cooling capacity. Due to their high efficiency and greater power reserves, conventional compressor cooling systems maintain supremacy for conventional refrigerators and freezers such as those found in the home and in laboratories.
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