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REVIEW OF THERMOELECTRIC COOLING DEVICES RECENT APPLICATIONS

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Abstract

Thermoelectric cooling (TEC) is being implemented in many applications due to its small component size, low cost, and environmental friendliness. This component, which produces a temperature gradient when applied with DC current, has been discussed in many reviews. This paper discusses many issues related to TEC. First, the factors that affect this component, such as the figure of merit, usage, influencing factors, and cooling capacity, are presented. Second, the coefficient of performance, which is the most important parameter that shows how a TEC device works effectively, is introduced. TEC devices are reliable and require no mechanical moving parts. They are small and environmentally friendly. Third, TEC structures and their numerous thermodynamic equations are described. The properties of TEC devices and the application of such devices are also discussed briefly. Finally, the use of a TEC device as a generating device or a thermoelectric generator (TEG) is investigated even though TEC and TEG are completely contradictory. TEG produces current when the temperature is applied. This study concludes that TEC is a good and reliable device that can be implemented in many applications. In addition, TEC has a good utilization potential in the electronics field because it can be controlled easily via its input voltage and current.

Keywords: Applications, Cooling, Refrigeration, Sensors, TEC, Thermoelectric.

1. Introduction

Electrical materials in life can be divided into three categories, namely, conductors, semiconductors, and insulators, on the basis of their capability to conduct electricity. Semiconductor devices play a major role in industries because their central components are used to process electrical signals that arise in communication, computation, and control systems. Semiconductors are deployed in many applications, such as small chips in computers and TV screens. They can also be used in small devices, such as thermal electrical cooling. TEC generates temperature gradients when fed with electrical power, and it has many advantages and applications.

This paper is arranged as follows. A table of the symbols used in this review is presented, followed by an introduction of the parameters used in TEC, their formulas, and their application areas. A short description of thermo-electric structures and their physical components, properties, and work principle are provided. The advantages of using this device and the main parameters, such as the coefficient of performance (COP) and cooling capacity, are discussed. A brief description of the physical components of thermo-elements and their effect on improving COP and cooling capacity is also provided. Moreover, numerous applications that use TEC are discussed. The first one is the use of TEC as a small refrigerator, which represents its basic working principle wherein low temperature is generated when DC current is applied. This application is for a picnic or personal purposes. The second application uses TEC to cool electronic chips, which are widely utilized in PCs and office equipment. The last application uses TEC as a sensor for sensing different things, such as fluid, motion, or heat.

2. Review of Thermoelectric Cooling Parameters

The parameters of TEC must be reviewed because they affect this device and its usage. These parameters are the figure of merit, cooling capacity, and COP.

2.1. Figure of merit

The figure of merit is denoted by (Z_t), and it is the main parameter used in describing the usefulness of the TEC material of refrigerators. It is a dimensionless product and is equal to:

$$Zt = \frac{\alpha^2}{\rho.k}, \text{ or } Zt = \frac{\alpha^2 \sigma}{k} \tag{1}$$

As indicated in Eq. (1), the figure of merit basically depends on α (Seebeck coefficient), ρ (electrical resistivity), and K (thermal conductivity) [1]. The figure of merit (Z_t) also depends on the TEC structure of its conductors, semiconductors, or insulators, and it can be considered zero, small, and large band gaps. To maximize Z_t, α should be maximized and p and k should be minimized. The figure of merit can also be regarded as temperature-dependent because each of the semiconductor materials' properties varies as a function of time. Multistage TEC can be used in applications that require a wide range of temperatures, and the figure of merit is ideal for single-stage *N*- and *P*-type applications [2].

Ideally, Z_t must be equal to 1; if so, it can provide the best low temperature for thermoelectric materials. Thermoelectric devices can be regarded as insufficient when Z_t =1, can recover waste heat when $Z_t = 2$, and can match refrigerators when $Z_t = 5/4$ [3].

The figure of merit shows the efficiency of *N*-type and *P*-type materials of TEC devices. A high figure of merit equates to high capacity to carry power for obtaining low temperatures. A high figure of merit also means high convenience of the device used. The value of the figure of merit changes according to the application; for example, it is equal to 1 in thermoelectric applications (cooling/heating) and equal to 0.25 in air-conditioning applications. Its effect is manifested in the maximum temperature difference and COP [3].

2.2. Cooling capacity

Cooling capacity results from the energy balanced from the cold side of TEC devices and is equal to [3]:

$$Qc = \alpha ITc - \frac{1}{2} ReI^2 - K\Delta T \tag{2}$$

Three main terms in Eq. (2) describe cooling capacity, and these three are Qg, Qj, and Qd. The term αITc is equivalent to Qg, and it is the amount of heat pumped at the cold side junction depending on the Seebeck coefficient, applied current, and temperature of the cold side of TEC. The term ReI^2, which is equivalent to Qj, is joule heat and depends on the electrical resistance and applied current. The term $K\Delta T$ is called Qd, which describes the heat transfer from the hot side to the cold side; it depends on thermal conductivity and the temperature difference between the plates of this device.

Many reviews have discussed cooling capacity. Chein and Huang [4] reviewed the applications of TEC and used temperature difference and cooling capacity requirements as parameters. The results indicated that the cooling capacity increases as the cold temperature increased and the temperature difference decreases. They also found that the maximum cooling capacity is 207 W, and the chip junction temperature is 88 ºC.

2.3. COP

Another parameter used to describe the efficiency of TEC is COP, which is equal to:

$$Cop = \frac{Qp}{Qte} \tag{3}$$

where Qp is the heat pumping capacity of TEC and equal to:

$$Qp = 2\,N\,(\,\alpha\,I\,Tc - \frac{I^2}{2\,G} - K\,\Delta T\,G\,) \tag{4}$$

From Eq. (4), it depends on the number of couples, applied current, Seebeck coefficient, the temperature at the cold side of TEC in *K*, difference temperature between two plates, and ratio of cross-sectional area/length of each TEC element.

Qte is the amount of heat dissipated by TEC, and it is equal to [1]:

$$Qte = 2\,N\,(\frac{I^2\rho}{G} + \alpha\,I\,\Delta T) \tag{5}$$

This amount of heat, which represents in Eq. (5) depends on the number of couples, applied current, electrical resistivity, the ratio of cross-sectional area/length of each TEC element, Seebeck coefficient, and the temperature difference between the plates of the TEC device. In any device, a high COP is always good. To increase COP, *Qp* must increase and *Qte* must decrease by changing the parameters of both.

The performance of most thermoelectric devices suffers from a low overall COP. Weerasinghe and Hughes [5] attributed this reduction in COP to losses in the thermal passage of many devices. Studies on this area have shown that performance can be improved by insulating the device well and arranging the thermal paths carefully.

A short review by Min and Rowe [6] showed the effect of thermo-element length on COP. They concluded that a decrease in thermo-elements results in a reduction in COP. For a given thermo-element, COP improves considerably when contact resistance or thermal contact resistance decreases. Cheng and Shih [7] performed a review to maximize cooling capacity and COP by using the genetic algorithm (GA). They adopted two stages of TEC cascade and studied the effect of this on cooling capacity and COP. They concluded that cooling capacity and COP demonstrate a remarkable improvement when two-stage TEC with slightly tuned parameters is used.

Other reviews have been conducted in relation to the improved performance of thermoelectric devices. Lin and Yu [8] used trapezoid-type two-stage Peltier coupled units for two-stage TEC instead of ceramic plates. They used this method to reduce inter-stage thermal resistance, which can improve the operation of TEC. Their simulation results showed that an optimum configuration of the trapezoid-type two-stage Peltier couples can provide maximum cooling capacity and COP under given operating conditions.

In practice, two-stage TEC has a larger temperature difference between the heat source and heat sink than single-stage TEC. A short review [9] used a pyramid-type multi-stage cooler to obtain the maximum COP, and thermal resistance was adopted as the key parameter. The authors concluded that the thermal resistance at the hot side of the heat sink is the main parameter that controls the overall performance of multistage TEC. The following Table 1 summarizes the main parameters that affect the performance of TEC.

Table 1. Summary of the parameters affecting TEC.

Parameter	Full name	Principle	Effect on TEC
Zt	Figure of merit	Describes the usefulness of the TEC material of refrigerators	A high figure of merit equates to high capacity to carry power for obtaining low temperatures
Qc	Cooling capacity	Results from the energy balanced from the cold side of TEC devices	As this parameter increases, it generates a reduced temperature difference
COP	Coefficient of performance	Describes the efficiency of TEC	A high COP means a sufficient TEC

3. TEC Structure

TEC is a reliable electronic device because it has no moving parts. TEC consists of modules, each of which has two plates made of ceramic or aluminium. Figure 1 shows a diagram of a single pair of *N*-type and *P*-type TEC device. PN junctions of *P*-type thermoelectric semiconductor materials and *N*-type thermoelectric semiconductor materials connected thermally in parallel and electrically in series exist between the plates, as shown in Fig. 2, thus, forming single-stage TEC.

Its working principle is similar to that of a small refrigerator or heat pump depending on the application. It uses the Peltier effect (related to the discoverer). When DC current goes through it, one side becomes cold, and the other side remains hot. In this way, a cooling temperature is generated, and the heat sink is used on the hot side to keep the generated heat from the cold side cool [10]. Commercially used multi-couple thermoelectric devices are of two types.

Figure 2 diagrams of multi-couple thermoelectric modules: (a) Type A configuration with ceramic insulating plates and large inter-thermo-element separation. (b) Type B configuration without a ceramic insulating plate and with very small inter-thermo-element separation [11].

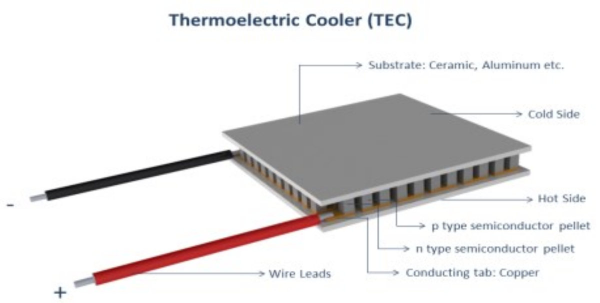

Fig. 1. Components of a thermal electric cooler [12].

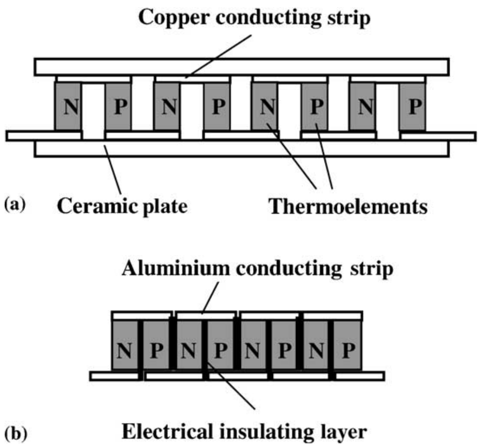

Fig. 2. Multi-couple thermoelectric modules.

Control work of TEC

Control of the TEC component is important because it affects the entire application that uses it; thermoelectric coolers are usually controlled by varying the voltage/current [13]. Mirmanto et al. [14] conducted an experiment on the performance of a thermoelectric cooler box with thermoelectric position variations.

Several thermoelectric positions were applied to determine the best one. TEC's module was TEC1-12706. The system consisted of a bottle of water, a heat sink fan, and an inner heat sink. The TEC was set in three locations: on the top, on the bottom, and on the wall. This experiment was conducted in an open setting with ambient temperature, and the power was constant at 38.08 W. The results showed that COP decreases with time, and the best location for TEC is on the wall.

This study is a good example of controlling TEC. In addition, the researchers introduced two main equations of COP describing the control of TEC based on thermodynamic theories, which are:

$$COP = \frac{Qc}{P}, \tag{6}$$

where *Qc* is the cooling capacity that was described in the previous section and *P* is the input power that is equal to the current-voltage applied. Given that these parameters serve as the input, they are the main controllable elements of TEC.

$$COPc = \frac{Tc}{Th - Tc} \tag{7}$$

Equation (7) describes the Carnot coefficient of performance, where *Tc* is the temperature at the cold side of the TE and *Th* is the temperature at the hot side. The coefficient of performance is affected by the temperature of the cold and hot sides. In other words, it increases as the difference temperature narrows.

The selection of the heat sink for the hot and cold sides of a thermoelectric device is the most important issue for overall performance. One of the most frequently used heat sinks in different applications is the mini-channel; this type of heat sink is also widely used in passive cooling applications because of its high efficiency [15].

Two main issues arise in generating the temperature in TEC. The first issue is the phenomenon called "Peltier effect," and the second is the "temperature guardian" when TEC is fed by a voltage difference. Both issues are discussed briefly in this research.

The Peltier effect can be considered the basis of the working principle of most modern thermoelectric devices for cooling or heating applications, and the Seebeck coefficient is the basis for power generation applications [16]. The Peltier effect can be summarized as follows: when TEC is fed with DC, the electrons go from the *N*-type semiconductor material to the *P*-type semiconductor material; the temperature of the interconnecting material starts to decrease, and heat is observed from the surroundings. This observation emerges when the electrons move from the low-energy *P*-type material to the high-energy *N*-type material through the interconnecting material. When the electrons pass through the low-energy *P*-type semiconductor material, they go to the other side of the junction and begin liberating. This scenario results in heat transfer through the semiconductor material, and this phenomenon is called the Peltier effect.

The other phenomenon that is important to TEC is the voltage generated when a temperature difference is created between the two plates of the semiconductor material. This voltage is known as Seebeck voltage, and it is directly proportional to the temperature guardian and the constant of proportionality, which is called the figure of merit (denoted by *Zt*).

For TEC devices, two terms are related to the temperature generated: a hot effect that arises when the current passes from the *P*-type semiconductor material and a cold effect that arises when the current passes from the *N*-type semiconductor material. The direction of the current decides whether the effect will be hot or cold.

The Peltier effect can be controlled by the Peltier coefficient, which is equal to the product of the Seebeck coefficient and absolute temperature. This coefficient depends on cooling and heating effects.

In ideal cases, the amount of heat dissipated on the cold side and the amount of cold temperature at the cold side depends on the current passing through the semiconductor material and the Peltier effect. However, in practice, the two sources are joule and conducted heat. Therefore, the amount of net heat generated for TEC by the Peltier effect is reduced by these two sources.

At the point where no further cooling occurs or the point of saturation, maximum current $Imax$ can be achieved. At this point, maximum temperature difference $\Delta Tmax$ and maximum voltage $Vmax$ can be obtained at any given load. One of the important parameters that many manufacturers attempt to improve is COP, which is also regarded as efficiency. In TEC, the input power is electrical energy, and the output is temperature. Therefore, COP is equal to temperature gradients divided by electrical energy; however, the complex relationship between the figure of merit and its parameters makes it and efficiency difficult to maximize [17].

However, a review by Huang et al. [18] mentioned that efficiency can be improved without using the figure of merit. The study examined the Thomas effect on TEC and its performance. Their results showed that cooling efficiency cannot be increased merely by increasing the figure of merit; the Thomas effect must also be considered.

TEC must be integrated with a phase change material (PCM), which stores cold thermal energy at night and operates as a heat sink during the day. Using this method improves the performance efficiency of TEC. This system can work in two modes: mode 1 that dissipates the generated heat to outdoor air by using an air-water heat exchanger and mode 2 that dissipates the heat to the shell and tube PCM, which is a heat storage unit. The experiment of Tan and Zhao [19] showed that COP increases by 56% when this method is applied.

4. TEC Properties

Thermal electricity is a phenomenon that produces heat from a DC power supply and vice versa by using the Peltier effect. Heat with low efficiency can generate TEC quality depending on parameters, such as the currents applied, temperatures of the plates, and contact resistance between the cold side and the surface of the device [3]. The performance and efficiency of TEC can be described with many parameters, such COP and cooling capacity. This work focuses on these parameters, especially COP [3].

Briefly, cooling capacity deals with thermal and electric constant resistances, and it depends on COP, the thickness of the constant layer, the conductivity of the thermo-element, and contact layers; the maximum temperature difference at cooling capacity is equal to zero [3]. To increase the reliability of TEC, manufacturers usually use multistage TEC, and in this case, cooling capacity is increased compared with single-stage TEC [3]. COP (energy efficiency) is used to measure the useful output in relation to the electric energy input, however, COP is small for TEC.

Many studies have dealt with thermo-electric parameters and improved them. Riffat and Ma [2] studied the physical component of thermo-electric parameters and the design effect on COP and cooling capacity. As the size of the thermo-element increases, a large COP is produced; however, for contact resistance, it should be as small as possible to improve COP and cooling capacity [3].

TEC has advantages over other electronic devices, including its small size, small weight, and absence of working fluid, which reduces maintenance costs and easily switches between cooling and heating modes [20]. TEC can also work off-grid with no moving parts, noise, or vibration; it is also easy to maintain [21]. In recent years, TEC has achieved remarkable progress in different areas, such as the military, industries, and domestic aerospace, due to its advantages over other electronic devices. These advantages include the following:

- TEC has no moving parts and thus, needs less maintenance compared with other devices.
- Experts' experience on this device shows that TEC has around 10,000 hours of steady-state operation.
- TEC devices do not contain any chemical material that requires periodic renovation.
- TEC devices do not relate to the position they are used in, and they can be used in any place at any time.
- Thermoelectric devices can be used in very small, sensitive environments as conventional refrigerators due to their small size.
- TEC can also be utilized for thermoelectric heating because it uses a DC source. The polarity and the direction of the current can be reversed to change TEC's operation.
- Thermoelectric devices can also be also used to control temperatures by adopting appropriate support devices.

According to applications of TEC devices, TEC can be divided into three main categories, namely, thermoelectric cooling or heating, the thermoelectric generation that generates electrical energy, and thermoelectric used as a thermal energy sensor [2].

The interest in power generation and refrigerators for TEC began in the 1990s when it was used for military and industrial purposes. Afterwards, due to its small size and safety, TEC was used in the electronics field for cooling infrared diodes and detectors [16].

5. TEC Applications

The use of TEC in applications was limited until semiconductor materials were developed. Afterwards, the applications of TEC increased. The characteristics and parameters of TEC should be improved before it can be used in many applications. Given that thermoelectric devices are classified into cooling, heating, and power generation, the two types of thermoelectric devices are also based on this. Type A-TEC is designed for cooling/heating purposes, and it has a significant separation between thermoelectric elements. This type includes highly conducting metal strips that are used to connect *N*-type and *P*-type semiconductors, which are electrically connected in series and sandwiched between thermally connected but electrically insulating plates. Type B is related to power generation applications and has a few separations in the thermoelectric element to increase the power generated. Here, metal strips are not insulated, and the module cannot be connected directly to the electrical conductor, such as aluminium heat sink [22].

TEC devices act like refrigerators or heat pumps according to the application used. Therefore, the laws of thermodynamics used for vapour compressors and mechanical heat pumps can be used for these devices. Moreover, TEC devices cannot be used alone; they should be connected to a heat dissipating medium and a heat exchanger [2].

5.1. Limitations in the use of thermoelectric technology in applications

Although thermoelectric technology has a promising future in the industrial field, this technology has many limitations. Many studies have discussed these limitations. Twaha et al. [23] presented a comprehensive review of thermoelectric technology, including its materials, applications, modelling, and performance improvement. They mentioned that the limitation of this technology is its low efficiency due to the low figure of merit (Zt) of the material used in making it. This is the main and most important limitation. Another limitation is that the input current is considered DC current and could cause problems because most of the new power sources are AC. Additionally, DC resources are limited and intermitted.

Another limitation due to the physical structure of TEC is the narrow distance between the hot and cold sides, which causes a problem in large-scale applications because no thermal isolation is available, and this sometimes helps transfer the temperature.

5.2. Applications of thermoelectric technology

Many researchers have discussed the use of TEC for industrial and domestic applications. Riffat and Ma [2] described TEC devices as solid-state devices without noise, vibration, and moving parts, and these reliable devices can be used anywhere due to their small weight.

They discussed the use of TEC as small refrigerators (cooler boxes) despite its small COP. Simons and Chu [1] reviewed TEC, its current development, and its application in cooling electronic equipment, such as infrared diodes and temperature-controlled enclosures.

They also presented the experience of IBM in cooling electronic devices by using optical diodes emitting light in two stages of TEC. They noticed that this device rejects air and cools small electronic devices. They concluded that TEC unless it demonstrates good improvements in COP, cannot meet the requirements of manufacturers and cannot be used for high-performance electronic cooling applications.

A short review [12] briefly discussed the application of TEC from the telecommunication point of view. It described the use of TEC for temperature control of oscillators. Using this methodology, we can increase the temperature easily or remove the heat of an oscillator. The chart is shown in Fig. 3 clarifies the main applications that use the TEC component for better understanding.

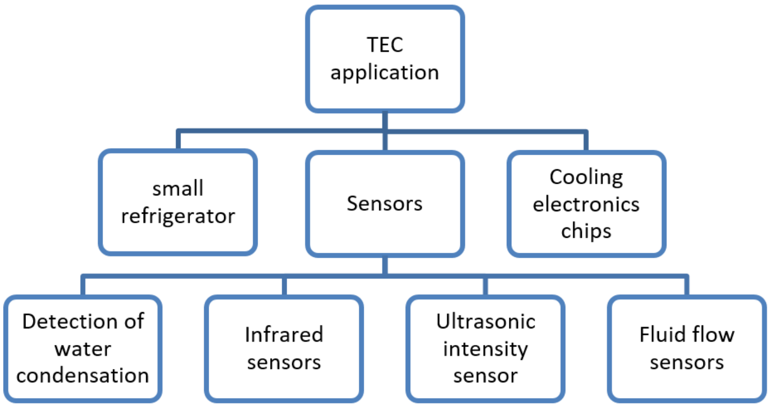

Fig. 3. Block diagram of main applications that use TEC.

• TEC as a small refrigerator

The use of thermoelectric as a cooling device is rampant in domestic, industrial, and personal applications, as shown in Fig. 4.

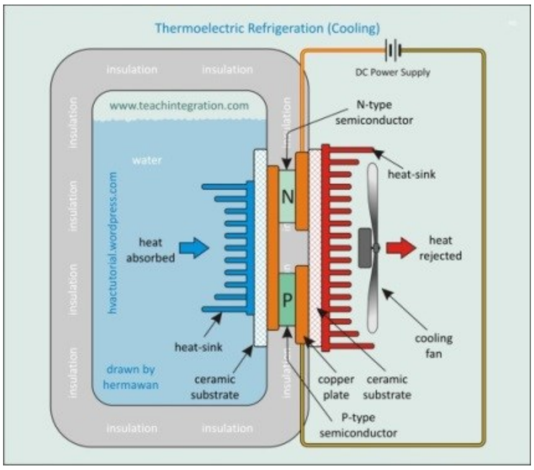

Fig. 4. Diagram of thermoelectric as a small refrigerator [12].

Applications that need high thermal capacity are limited due to the reduction in COP and high energy cost. Current thermoelectric devices have COP < 0.5 at a temperature difference of approximately 20 ºC Given that COP is lower in TEC devices than in other electronic devices, TEC devices are used for niche applications that are below 25 W (military application) and for applications that require a specific criterion, such as small size, small weight, high reliability, and compatibility with electrical and industrial environments [11].

In recent years, Earth's temperature has been increasing due to the increase in population. Therefore, the use of refrigerators and air-conditioning units has increased remarkably. Population growth, high living costs, and the increase in CFCs have motivated manufacturers to start seeking for an alternative energy source that provides a clean, cheap, noiseless, reliable, and environmentally friendly technology; all of these characteristics are present in one small electronic device, which is the thermoelectric cooler [24].

The use of TEC as a cooler provides buildings with a thermoelectric cooling system, which is basically made of an electric circuit consisting of a power source that provides DC current and at least one heat sink and one heat source to cool to the desired temperature range.

A conventional refrigerator system consists of an evaporator, a compressor, and a condenser. A TEC system is analogous to this system, except that TEC uses the Peltier effect to eliminate the heat from the electronic components, and its range of use comes from cooling electronic chips to air conditions for domestic applications. The first use of the thermoelectric device for cooling was from 1950 to 1960. However, because of the reduction in COP, the development and application of TEC have been limited. In recent years, the use of TEC for small applications, such as military and domestic ones, has increased for unknown reasons.

The use of TEC for air conditioning was first introduced in 1960 for cooling or heating small living rooms, restaurants, and offices. The use of TEC devices for air conditioning exhibits many advantages over the use of conventional air conditioning, which utilizes compressed gas. These advantages are as follows. TEC devices can be connected to PV panels without any conversion because they use DC current and are low-voltage-driven devices.

TEC devices can also be built with a very flat unit, which can be wall-mounted, and can be easily switched between heating and cooling modes and adjusted to meet the requirements of the device individually. These features make the use of TEC devices as air conditioner very compatible with the use of small building air conditioner.

Current commercial products, which are consumer products of TEC devices, are available as recreational vehicle refrigerators, water coolers or portal picnic coolers, car refrigerators, motorcycle helmet refrigerators, and insulin coolers (portable).

TEC can also be used for certain human services, such as in hotels (small refrigerators used in rooms), vehicles (air conditioning), aircraft (cooling water for drinking), cooling equipment in the medical field, marine equipment, and restaurant equipment (e.g., dispensers for butter or cream) [11]. Table 2 shows the main difference between a conventional refrigerator and a thermoelectric refrigerator.

Table 2. Conventional and thermoelectric refrigerators.

	Thermoelectric refrigerator	Conventional refrigerator
Work principle	Depends on the Peltier effect	Equilibrium phenomenon
Size	Very small size, can be moved to any place	Large size and must be put in one place
Cost	Low cost	High cost
Efficiency	Low efficiency	High efficiency
Complexity	Simple and easy to use	Complex and sometimes dangerous
Lifespan	200,000 hours	Around 10 years

• TEC for cooling electronic chips

In addition to the use of TEC as a refrigerator, it can also be used for another important application, which is cooling electronic chips and components. Given that the conventional cooler is unsuitable for small and soft components, TEC is prioritized in this field. The applications of TEC as a cooling device for electronic components have increased remarkably in recent years, and some of them are described briefly in this review. In upcoming applications, electronic components are cooled by directly focusing on the cold side of one or more thermoelectric devices. Doing so allows the largest amount of heat to be transferred between the electronic component and the cold side of the thermoelectric device.

The resulting heat is coupled to the heat sink, and water is usually used to remove the heat from the heat sink. Alternatively, natural conservation schemes, such as the use of various sources of DC current to reduce temperature, can be utilized to decrease the heating of electronic components. The use of TEC devices for cooling electronic components requires a low DC current thermoelectric device. A general-purpose and low-cost version of this device is commercially available for laboratory cooling instruments and apparatus. One of the popular devices that are widely used is frigi-chip cp, which is a series of thermoelectric devices provided by MELCOR**.** Figure 4 shows the use of TEC for cooling infrared electronic components. Figure 5 shows diagrams of an integrated thermoelectric micro-cooler with infrared components integrated into the cooled central region: (a) plane view and (b) cross-sectional view [11].

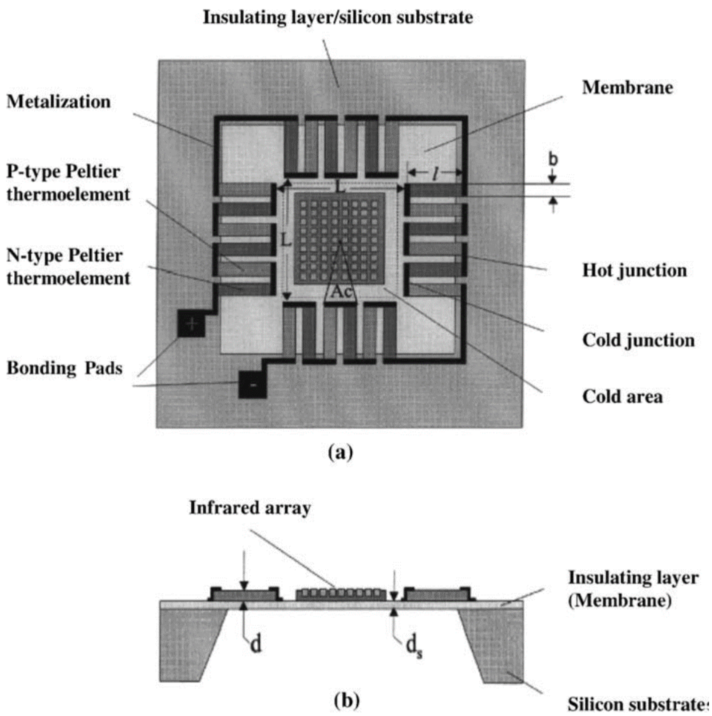

Fig. 5. Integrated thermoelectric micro-cooler [11].

Several general cases integrate the cooling of components that use thermoelectric devices into small applications. For example, microelectronic manufacturers create integrated circuits, however, conventional thermoelectric devices cannot be used in this field because they are incompatible with small microelectronic chips and the integrated circuit manufacturing process. Therefore, the micromachining technology that is used to design thin-film thermoelectric coolers can be coupled with micro-electric circuits. These applications simply involve cooling infrared detectors, removing unused disturbances from the integrated circuit, and helping stabilize the temperature of laser diodes.

A thin film usually passes through production steps before integration with microelectronic circuits as follows. Conventional thin-film deposition is used to make a very thin amorphous SiC film laid down on a silicon substrate. By removing the silicon substrate in the desired regions, a membrane can be formed, and micromachining can be used for this purpose. A membrane is produced to deposit *N*-type and *P*-type materials on it and form thermocouples. These thermocouples are configured and surround the central regions to be cooled by the cold junction. The rest of the silicon substrate rim contains the hot junction of the thermocouples. Afterwards, the heat equilibrium of this device starts to develop, and the heat starts to move from the central regions to the silicon substrate rim; the rest of the heat is removed by the heat sink [25].

Electronic devices usually produce heat during normal operation, and they must be kept at ambient temperature. The importance of using this device arises here. The main purpose of using thermoelectric arranged as a super cooler is to remove the heat produced by electronic devices and keep it at a normal operating value. Another use of thermoelectric devices is to reduce the leakage current from electronic devices and thermal noise from electrical components. This method is adopted to improve the accuracy of electronic devices [26, 27]. This use is for small-capacity applications, such as 3 W, and the leakage current of the detectors must be reduced to allow the use of pulse shaping times for long periods, which in turn improves the energy resolution.

The commercial products that use thermoelectric as a cooler for electronic components are laser diode coolers, integrated circuit coolers, cold plates used in laboratories, cold chambers, photomultiplier tube-housing coolers, stairs, immersion, electrophoresis cell coolers, and devices that need a large amount of cooling (e.g., charge-coupled and charge-induced devices). Table 3 shows a brief comparison of a TEC device and other cooling devices and indicates that the TEC device can be prioritized for use, although its low COP reduces its application.

Table 3. Comparison of cooling devices.

	Thermoelectric cooling	**Other cooling devices**
Cost	Low cost	Relatively high cost
COP	Low COP	High COP
Size	Very small size	Medium or large
Power source	DC power source, off-grid	AC power source, on-grid
Weight	Small weight	Large weight
Environment friendliness	Clean and safe to use	Produces a CFC gas that is dangerous

• Use of TEC as a sensor

Another useful application of the TEC device is as an energy sensor that is based on the Peltier effect. This type of sensor is better than the conventional sensor. Many commercial thermoelectric products are available in this field, such as the temperature control used in the industrial field. The most famous product is the NEMA enclosure, a microprocessor and numerical control that is used in PCs and robotics. It provides the stability of the ink temperature for printers and copiers. The thermoelectric energy sensors used in industrial applications are ultrasonic intensity sensors, cryogenic heat flux, infrared sensors, and fluid flow sensors.

Several of them are described briefly in this review. A measurement system for milk fat content is designed and realized based on optical fibre sensor and thermoelectric cooler. The main components of the system include also a light source, *Y*-type optical fibre, photodetector, amplifier circuits, A/D converter, microprocessor, data storage module, data display and key module. The system based on Mie light scattering theory of the absorbency that adopted as the optical parameter to indicate the milk fat content. TEC realize Homogenization to ensure that the scattering coefficient keeps invariant. The results indicate the feasibility and real-time performance of using this measurement system for milk fat analysis [28].

• Ultrasonic intensity sensor

In recent research and experiments, thermoelectric ultrasonic sensors have taken the role of measuring intensity, and they have been used in chemical reactions and mass transfers in the laboratory. Figure 6 shows the working principle of an ultrasonic sensor. A thermoelectric ultrasonic sensor is designed using an observing material, such as silicon (Si), and multiple thermocouples are embedded along with the silicon. Here, two rack gears are used. The first one provides horizontal and vertical accuracy displacement. The second one is used inside the ultrasonic cleaner and allows for precise positioning of the reactor. Through heating and the temperature increase in the silicon that works as an observation material, it is linked to the absorption of ultrasound when it is transmitted in the medium. The stopping of the ultrasound emission causes the temperature to decrease.

A review by Romdhane et al. [29] described the use of thermoelectric as an ultrasonic sensor. Their results showed that the modelling of heat transfer allows the establishment of the relationship between ultrasonic intensity and the temperature signal response of the probe.

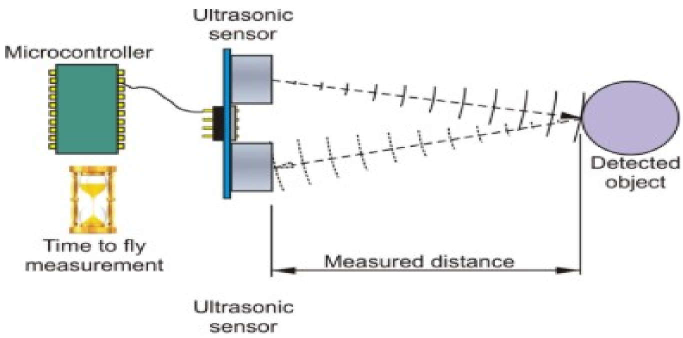

Fig. 6. Working principle of an ultrasonic intensity sensor [30].

• Infrared sensors

This type of thermoelectric sensor, which shown in Fig. 7 uses infrared waves. Therefore, it is used in contactless sensing of temperatures, such as passive alarm sensors and infrared gas analysis. This sensor is highly sensitive to infrared rays and used for detecting motion. It can be divided into two types (thermal and photon IR sensors) based on its detection mechanism. In a thermal sensor, the sensor observes radiation and converts it into thermal energy. The magnitude of the infrared radiation signal is measured based on the increase in temperature because as the thermal energy product increases, the temperature of the sensitive component increases. Meanwhile, a photon IR sensor works when the detector observes photons.

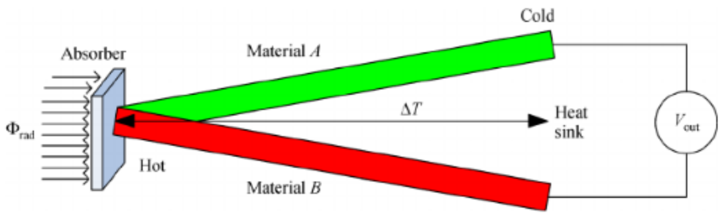

Fig. 7. Working principle of MEMS-based thermoelectric IR sensor. (Output voltage, V_{out}, generated when IR radiation flux, F_{rad}, irradiates sensor [31].

• Fluid flow sensors

Another type of thermoelectric sensor shown in Fig. 8 is the fluid flow sensor. This type is used for sensing low-velocity fluid flows [32], and it can be classified into thermal and non-thermal sensors. Thermal sensors have been investigated extensively due to their simple structure and implementation, low power consumption, high resistivity, ease of fabrication, and lack of moving parts compared with non-thermal flow sensors [33]. The main advantage of this device is that natural convection or thermal perturbation is negligible because the average temperature is almost similar to the fluid temperature.

Fig. 8. Diagram of a fluid flow sensor [34].

To measure low-velocity fluid flow, a new sensor and method were proposed based on the use of the Peltier effect to generate a temperature difference between numerous thermoelectric junctions along a wire. The thermal gradients were detected using the Seebeck effect. The results showed that the proposed device can withstand many applications [32].

- **Detection of water condensation**

The last type of thermoelectric sensor involves the detection of water condensation. This sensor is a type of integrated micro-sensor that detects water condensation. Its operation depends on the Peltier effect when it generates oscillation as follows: when the oscillation becomes a disturbance, water droplets are formed upon cooling of the junction at the sensitive field; this produces a frequency shifting that allows manufacturers to determine the conditions of mist formation. To operate this micro-sensor, interfaced electronics should be designed to generate and control thermal oscillation [35].

Table 4 presents a brief comparison of the applications of TEC and other technologies. Notably, TEC is a preferable application in daily life because it needs only a DC source, which can be found easily in any place. In addition, it is small, cheap, clean, and safe to use compared with other technologies.

Table 4. Comparison of TEC and other technologies' applications.

	TEC applications	Applications implemented with different technologies
Power source	DC source, off-grid	AC source, on-grid
Size	Small sizes	Large sizes
Cost	Low cost	Expensive
Simplicity	Simple and easy to use	Complicated
Environment friendliness	Clean, safe, and environmentally friendly	Some of the applications produce toxic gases

Thermoelectric application as a power generator

In contrast to the thermoelectric cooler, a thermoelectric generator device produces a voltage difference when it is supplied by a temperature difference [36]. Owing to its high reliability, low cost, and environmental friendliness, it is adopted in many applications using thermoelectric generators, such as converting waste heat in power plants into electricity in extreme environments. It can be also used in industries, transport, and domestic purposes. Thermoelectric generators are also used in gas pipelines, remote off-grid power generation, and PV solar systems as a backup sensor [10, 37].

To understand the working principle of thermoelectric generation (TEG), a thermodynamic theory is discussed due to its dependency on thermodynamic equations [38].

$$\eta = \frac{Th-Tc}{Th}\frac{\sqrt{1+Zt}-1}{\sqrt{1+Zt}+Tc/Th} \tag{8}$$

Equation (8) describes the efficiency of energy conversion, which is directly related to Carnot efficiency and figure of merit (a dimensionless parameter as described in Eq. (1)). This equation indicates that efficiency is increased at the low-temperature range.

The efficiency of TEG refers to the electricity that could be gained from the application that uses TEG. Figure 9 describes TEG's three main parts, namely, thermoelectric generator, heat sink, and heat source. Figure 10 provides an example of waste heat recovery using TEG. This system includes 400 modules of TE, each of which, has 28 half-Hesuler-based TE uncouples. An automotive diesel engine with an electric power density of 1 kW is used for converting exhaust waste heat. In addition, the system has a DC-DC voltage booster. System efficiency is determined by the TEG subsystem, the means of joining the TEG parts and the heat source, and the means of heat dispersion at the heat sink (air or water cooling) [38].

Thermoelectric generators have received considerable attention in power systems due to their capability to convert waste heat into electricity [39]. The main advantages of this conversion energy device over conventional energy conversion devices are that it is easy to maintain because it has no moving part or vibration. It is also small and cheap. The main challenge is that it has low efficiency, which is why limited applications use it. However, it helps reject waste heat, so it is considered an environmentally friendly resource.

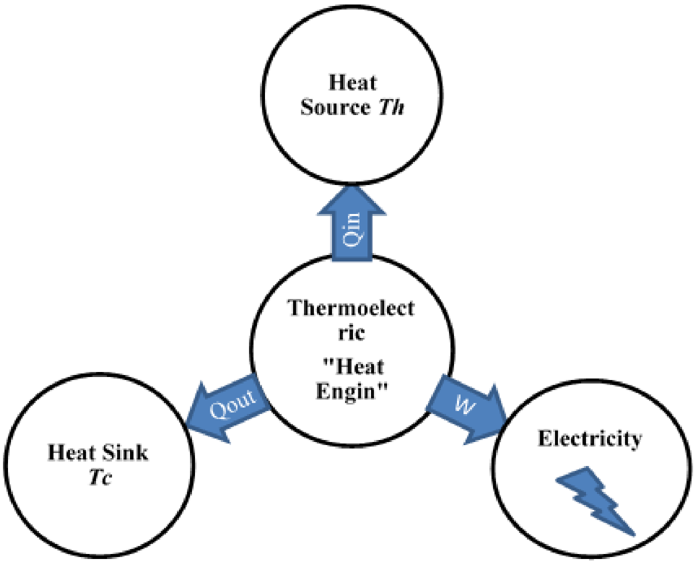

Fig. 9. Thermoelectric power generation: working principle.

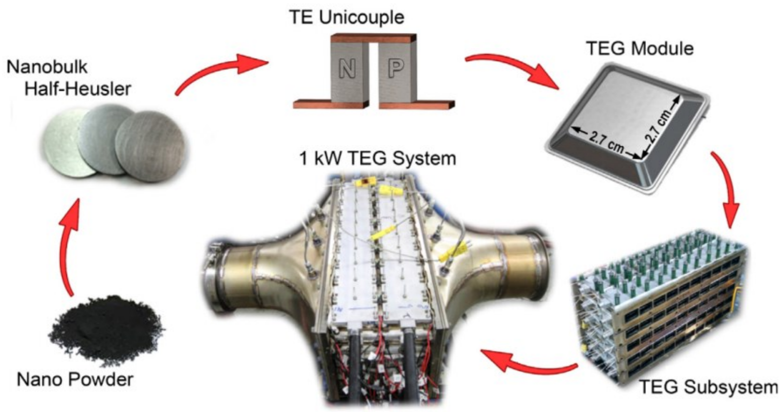

Fig. 10. Real TEG system for automotive waste heat recovery [40].

Figure 11 shows a TEG equivalent circuit that consists of a load resistance and an internal TEG resistance connected in series with the voltage source. This voltage source is equal to the open-circuit voltage, which is a function of the Seebeck coefficient and the number of thermocouples, therefore, the current passing through TEG is equal to:

$$Isc(TEG) = \frac{Voc(TEG)}{RTEG} \tag{9}$$

The new technology that uses TEGs is the hybrid system with the PV system that was applied by Al-Nimr et al. [21], who designed a bi-generator system combining a direct absorption flat plate solar collector for medium-temperature air-heating applications integrated with a thermoelectric generator to increase the electrical conversion efficiency of the TEG modules. This system was simulated under the effect of evaporative cooling at the cold side of the TE modules so that cooling effects can be created. These cooling effects will, in turn, decrease the temperature of the cold junction. Their results showed a significant effect on the electricity produced when TEGs were used, given that a 19.13% augmentation was predicted. Furthermore, the electricity performance of the system showed stability. Knowles and Lee [41] introduced two cycles for TEG. The first one was for a gas turbine as a topping cycle, and the second one was for a preheating cycle. Their results revealed that using many TEGs could improve the thermal efficiency of the combined system, especially for the turbines that have low temperatures.

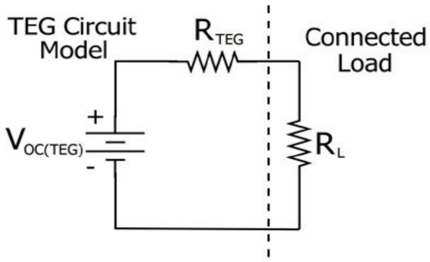

Fig. 11. TEG equivalent circuit [42].

6. Conclusion

Thermoelectric devices involve TEC and thermoelectric generation. This work focuses on TEC that generates a temperatures difference when it is supplied with electrical power due to the Peltier effect. TEC is preferable and has been used frequently in recent years because of its small weight, low cost, and environmental friendliness. TEC can work without being connected to a grid, and it has low noise and vibrations. It is also easy to maintain. The properties of thermo-elements and the main parameters, such as COP and cooling capacity, were discussed separately. The results showed that increasing the size and reducing the contact resistance improve both parameters. This review mentioned the applications used for this purpose. A limited application range was noted due to the low COP of TEC. Improvement of this parameter was discussed together with TEC applications, such as refrigerators, cooling for electronic components, and as a sensor. In addition, the use of thermoelectric devices in power generation was presented. TEG devices have the same structure as TEC and could have a high potential for use as a future power generation green source.

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Nomenclatures

G	Ratio of cross-sectional area/length of each TEC
I	Applied current
K	Thermal conductivity
N	Number of couples
Qp	Heat pumping capacity
Qte	Amount of heat dissipated by TEC
Re	Electrical resistance
T_c	Temperature at the cold side
Z_t	Figure of merit
Greek Symbols	
ΔT	Difference in temperature between two plates
α	Seebeck coefficient
ρ	Electrical resistivity

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