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Solid State Cooling and Heating : A Review on Technology and its Applications in Food and Agriculture

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ABSTRACT

Increasing power costs, environmental pollution and global warming are issues that we are dealing in the present time. To reduce their effects, scientists are focusing on improving energy harvesting-based solid state modules. Most of the research work done so far deals with an objective of low energy consumption and refrigeration effect enhancement. The present refrigeration system produces cooling effect by refrigerants like freon, ammonia, etc. Using these refrigerants, we can get maximum output but one of the major disadvantages is harmful gas emission and global warming. These problems can be addressed by using solid state (Peltier effect) refrigerators to protect the environment. Solid state refrigeration is one of the techniques used for producing refrigeration effect. Solid state devices and power generators are developed based on Peltier and Seebeck effect which has experienced a major advances and developments in recent years. The manuscript summarizes the work done, advancement in solid state cooling / heating, thermoelectric materials, design methodologies, applications in various fields and performance enhancement techniques based on the literature.

Keywords: Coefficient of performance, Figure of merit, Green houses, Peltier effect, Solid state cooling/heating

THE global increasing demand for refrigeration in the field of refrigeration air-conditioning, food preservation, agriculture, vaccine storages, medical services and cooling of electronic devices, led to production of more electricity and consequently more release of CO_2 all over the world which is contributing factor of global warming on climate change (Vaidya *et al.,* 2015 and Dongare *et al.,* 2018). In recent years, with the increasing awareness towards environmental degradation caused by CFCs and HCFCs from refrigerants in conventional refrigeration systems, it has become a subject of due concern (Praveen and Pranay, 2018). Solid state cooling is a new alternative because it can convert waste electricity into useful cooling and is expected to play an important role today. Thermoelectric cooling is a way to remove thermal energy from a medium, device or component by applying a voltage of constant polarity to a junction between dissimilar electrical conductors or semi conductors (Raheem *et al.,* 2018). Solid state refrigeration provides cooling effect by using thermoelectric effect *i.e.,* Peltier effect rather than the more prevalent conventional methods like those using the 'vapor compression cycle' or the 'gas compression cycle' (Awasthi and Mali, 2012).

Solid state cooling / heating finds applications in greenhouses, aqua hydrophonic systems, dryers, cold storages, refrigerators, dehumidifiers, air conditioners etc. To achieve controlled atmosphere. Solid state modules are environmental friendly because they do not contain chemical products, they operate silently because they do not have mechanical structures and moving parts and they can be fabricated on many types of substrates like silicon, polymers and ceramics (Ajithkumar *et al.,* 2014 and Rakesh *et al.,* 2016). Further, more solid state modules are position-independent, present a long operating lifetime and are suitable for integration into bulk and flexible devices (Jaziri *et al*., 2019).

Solid State Cooling Module (TEC) Basis

Solid state coolers are based on the Peltier effect and are commonly used to convert electrical energy into athermal energy. A basic solid state module consists of semi conductor elements (p-type and n-type) that work as two dissimilar conductors arranged in specific order reported by Beretta *et al.,* 2018. When the direct current passes through one pair or multiple pairs of elements from 'n' to 'p' the temperature will decrease at that junction, resulting the absorption of heat from the surrounding (Jaziri *et al*., 2019). The heat is carried out through the transportation of electron and it will move from high state to low state. The pumping capacity of a cooler is directly proportional to number of pairs of 'n' and 'p' type (couples) (Chavan and Dhawde, 2015). Solid state refrigeration system works on the thermoelectric effects such as : 1) Seebeck effect, 2) Thomson effect and 3) Peltier effect.

Thermoelectric Cooler (TEC) Fabrication

The first thermoelectric phenomenon was discovered by French Physicist and meteorologist Jean Peltier. The basic idea behind the Peltier effect is that whenever DC passes through the circuit of heterogeneous conductors, heat is either released or absorbed at the conductor's junctions, which depends on the current polarity. (Patil and Devade, 2015).

Solid State Cooling Modules: For producing thermoelectric effect, couples of p and n type semiconductors are connected in series by metal plates. By arranging the circuit as shown in Fig. 1, it is possible to release heat to the one side and absorb from another side. Using these special properties of the TE 'couple', it is possible to team many pellets together in rectangular arrays to create practical thermoelectric modules as shown in Fig. 2, when solid state p-n materials are connected electrically in series and

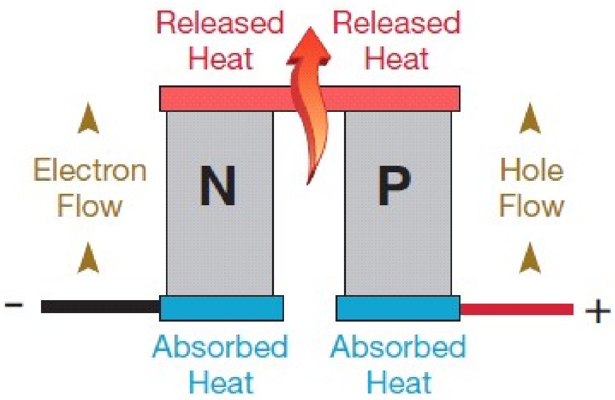


Fig.1: Peltier cooling by couple of n and p (Thakkar, 2016)

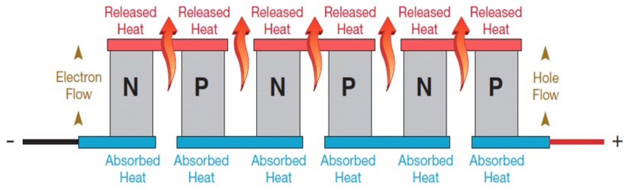


Fig. 2: Peltier cooling by multiple pallets (Thakkar, 2016)

thermally in parallel it makes one thermoelectric unit as shown in Fig. 3 (Thakkar, 2016; Beretta *et al.,* 2018).

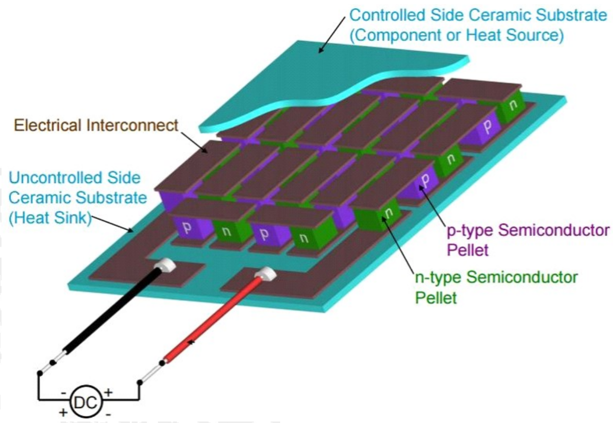


Fig. 3: Fabrication of Peltier module (Thakkar, 2016)

A typical thermoelectric (TEC) module comprises of two highly thermal conductive substrates ($A1_2O_3$, A_1N, BeO) that serve as hot / cold plates. An array of p-type and n-type semiconductor (Bi_2Te_2, Sb_2Te_3, Bi_2Se_3, PbTe, Si-Ge) pellets are connected electrically in series sandwiched between the substrates (Thakkar, 2016 and Beretta *et al.,* 2018). The device is normally attached to the cold side of the TEC module and a heat sink which is required for enhanced heat dissipation is attached to the hot side. Solder is normally used to connect the TEC elements onto the conducting pads of the substrates (Malik *et al.,* 2017). The construction of a single stage thermoelectric module is shown in Fig. 3.

Materials

The common thermoelectric material used in different applications are bismuth sulfide (Bi_2S_3), lead telluride (PbTe), antimony telluride (Sb_2Te_3), cesiumsulfide (CeS), bismuth telluride (Bi_2Te_2) and germanium telluride (GeTe). The Seebeck coefficient for different material are given in Table 1, of these, Bismuth telluride is the most commonly used andnew high-performance materials for thermoelectric cooling are being actively researched (Nair & Balakrishna, 2015; Gaikwad *et al*., 2016 and Malik *et al.,* 2017).

TABLE 1

Seebeck coefficient for different material

Material	α = Seebeck coefficient (K^{-1})
Germanium telluride	1.5×10^{-3}
Cesiumsulfide	1×10^{-3}
Bismuth telluride	41×10^{-8}
Lead telluride	1.5×10^{-3}

Figure of Merit

Figure of merit is a term used to define the performance of a thermoelectric device. It can be calculated using the equation;

$$ZT = \frac{\alpha^2}{\rho k} = \frac{\alpha^2 \sigma}{k}$$

where, α is the Seebeck coefficient in (V/K), ρ is the electrical resistivity in (Ωm), k is the thermal conductivity in (W/mK) and σ is the electrical conductivity in (mK/W). Recent innovations have proven to have a ZT value greater than 1 that defines the performance of a thermoelectric materials shown in Fig. 4 (Suryawanshi *et al.,* 2016). The higher the value of ZT, higher the energy conversion efficiency of the device. From equation (1), the interdependence of the parameters is very evident. In order for the figure of merit to be high, the seebeck coefficient α and the electrical conductivity σ must be high while

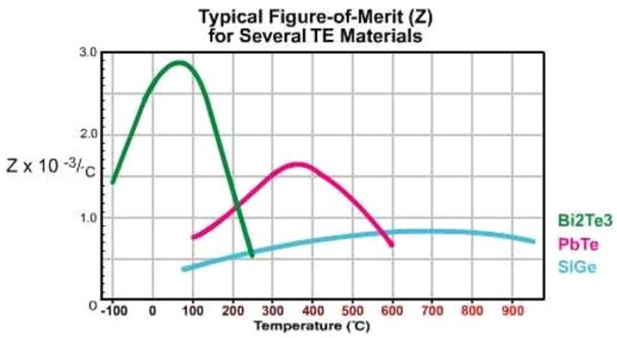


Fig. 4 : Figure of merit v/s temperature for typical thermoelectric structures

the thermal conductivity (k) must be low (Mani, 2016). The values of these parameters are the defining points in the performance of a thermoelectric system and it has been very difficult to model a device that satisfies this interdependence completely (Thakkar, 2016 and Rawat *et al.,* 2013).

Methodological Problems

Peltier module that has capacity to lower the temperature of the cooling heatsink to such a level that the moisture in the air condenses a dangerous situation for electronic circuits. Water constantly formed by condensation may cause the electronic circuits of any device to short-circuit. The distance should be maintained between wires and surfaces of the solid state modules to avoid short circuit (Hajovsky *et al.,* 2016). The heat/cold rejection is the difficult task while modules operating because of the gap between two surfaces. For getting efficient cold/heat, one energy should be rejected and sometimes use of both energies simultaneously will increase the performance of the solid state modules as like heat pumps. The quick change in the polarity of the module and getting both energy (cooling and heating) from same module and from same surface of module will shorten the life of the module (Al-Madhhachi and Min, 2017). The attachment of the heat sinks to both side of the module is a difficult task due to the thickness of the module. The more research work has to be done on the design of the solid state module by considering the present methodological problems.

Thermoelectric Today

Various types of thermoelectric modules are available in market like general purpose module, deep cooling module, multistage module, telecom grade modules, custom modules and high power modules. In food and agricultural sector, the general purpose modules are used because of its properties and low cost. Increasing material cost, lack of power supply, environmental pollutions and global warming are the issues in the food and agricultural sector. These problems can be addressed by using solid state (Peltier effect) refrigerators to protect the environment. Because of low COP, solid state cooling modules are restricted to the small capacity. The increase in load results in decrease of COP of the solid state module because of this reason the modules have various applications in small scale. More research is required on increasing the performance and ZT valve of the solid state modules.

Applications

Solid state devices are devices of the future. The applications of solid state cooling modules have so far been employed in many devices where the size of the device is small. In applications where the temperature needs to be stabilized, a cooling effect needs to be produced or heat up the device using a reverse current, thermoelectric cooling modules have been used.

Some of the other potential and current uses of solid state cooling are :

1. *Agriculture*: Greenhouse technology, aqua hydroponics, hydroponics and water condensation (Hung & Peng, 2017 and Hungerford, 2015)
2. *Food Applications*: Beverage cooler, dryer, controlled atmosphere storage, dehumidifier, distillation unit, rapid liquid cooler and dairy products cooler (Thakor *et al.,* 2015 and Hung & Peng, 2017)
3. *Military/Aerospace*: Inertial guidance systems, night vision equipment, electronic equipment cooling (Glatz *et al.,* 2009) cooled personal garments and portable refrigerators
4. *Consumer products*: Recreational vehicle refrigerators, mobile home refrigerators, portable picnic coolers, wine and beer keg coolers and residential water coolers/purifiers
5. *Laboratory and scientific equipment*: Infrared detectors, integrated circuit coolers, laboratory cold plates, cold chambers, ice point reference baths, dewpoint hygrometers, constant temperature baths, thermostat calibrating baths, laser collimators (Patil *et al.,* 2017)
6. Industrial equipment: Computer microprocessors, microprocessors and pc's in numerical control and robotics, medical instruments, hypothermia blankets, pharmaceutical refrigerators - portable and stationary, blood analysers, tissue preparation and storage, restaurant equipment, cream and butter dispensers (Thakkar, 2016)
7. *Miscellaneous*: Hotel room refrigerators, automobile mini-refrigerators, automobile seat cooler and aircraft drinking water coolers

Greenhouse Technology

The greenhouse have been improved and developed by using modern technologies in recent times. The manuscript describes the application of low power consumption and efficient device called thermoelectric devices in greenhouse. Hung and Peng, 2017 worked on application of thermoelectric cooling in water-autonomous greenhouse system. The researchers used solid state cooling modules for smart-green vertical greeningto reduce the surrounding temperature, thereby generating condensed water to drop irrigate the plants cultivated in the plantation trough (Fig. 5). The sunlight illumination further causes the temperature in the system to rise up is the major problem in the greenhouse such that the water molecules within the system may evaporate and wet, warm air is continuously heated and humidified (cooling/heating) (Hung and Peng, 2017). The main goal of the system is to make the temperature inside the greenhouse under control and provide the plants with appropriate environments to ensure healthy products (Shenan *et al.,* 2017). A plant ecological environment system that can be maintained autonomously by using thermoelectric technology but it holds good for low

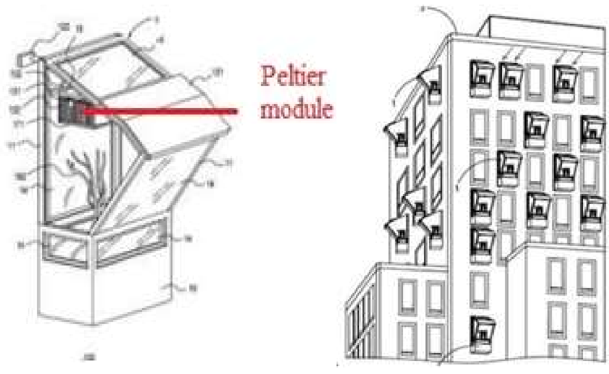


Fig. 5 : Drawings and major component of smart-green vertical greening.

cooling load, if cooling load increases the cooling efficiency (COP) of the solid state modules will reduce which effects on the plants surrounding temperature. With an appropriate closed-loop temperature control circuit, solid state coolers can control temperatures to better than +/- 0.1°C.

Wireless Sensor Networking (WSN) is proved to be a boon for Hi-Tech agricultural field used to monitor and control the climate. The WSN approach has a great potential for remote crop monitoring and control using WSN technology for large scale green house (Sumalan *et al.,* 2020 and Chaudhary *et al.,* 2011). WSN use a portable battery to power the sensors. To meet requirement, Vazhuthi *et al.,* 2019 utilised the solar energy and heat generated from the control gears in greenhouses to produce the electricity by using solid state modules. As per Seebeck effect the absorbed heat flows from hot junction to cold junction, the flow of heat drives the free electrons (e^-) and holes (h^+) producing electrical power from heat (Musleh *et al.,* 2017). Installation of control gears in greenhouses, heated during operation up to 200 °C separately from irradiators (Dolgikh *et al.,* 2019) allows using their thermal energy, converted into electrical energy using thermoelectric generator modules for driving fans. The quick change in the polarity of the module and getting both energy (electrical and thermal energy) from same module also shorten the life of the module, there must be a proper system to dissipatethe heat from other side of the module to get efficient cooling effect.

Natural water resources are creating ever-increasing obstacles for agricultural installations within many regions around the globe. However, within artificially created humid atmospheres such as greenhouses and hydroponics water can be condensed from the air and re-used instead of being completely wasted through open ventilation (Jradi *et al.,* 2012). Hungerford, 2015 and Atta, 2011, developed a completely regenerative permaculture cycle utilizing a proven aquaponics footprint powered by a solar energy array and sustained with a prototype thermoelectric air-to-air cooling water condensing system. The air can hold mixture of gases and water vapor. At a given temperature and pressure, there is a limited amount of water vapor that air can hold. When this limit is reached, air is considered saturated. when the mixture is introduced to cold surfaces of solid state modules, water vapor will condense, returning to liquid water (condenser chamber 1.2 m in length and 0.07 $\times$ 0.05 m^2 cross sectional area). Benefits of the condensing system produces is the aiding in humidity control within the greenhouse, helping to combat harmful pathogens (Hungerford, 2015). The condensed water vapor forms ice crystals on solid state module surface because the module has ability to reach below 0 °C at lower load which may results in short-circuit and also liquid water can cause deterioration or greatly reduce the performance of some materials in greenhouses.

Thermoelectric Dryer

During the last two decades, however, scientists have observed that the CFC and HFC refrigerants used in refrigerators and heat pumps are destroying the earth's ozone (O_3) layer (Rokde *et al.,* 2017). Thermoelectric heat pump drying system is an alternative to existing HFC hot-air drying systems.Wongsim *et al.,* 2015, worked on drying of laurel clock vine leaves using thermoelectric dying heat pump. The TE heat pump dry the leaves without use of any working fluid. Fig. 7 shows the schematic diagram of thermoelectric dryer and modules arrangement. The heat pump achieved 40 to 50 °C temperature to reduce the laurel clock vine leaves. For the drying tests, 30 g fresh laurel clock vine leaves with an initial moisture content of approximately 79.5 per cent (d.b.) is used for each drying test. The laurel clock vine leaves are dried to a moisture content of 7.5 per cent (d.b.) (Fig. 6).

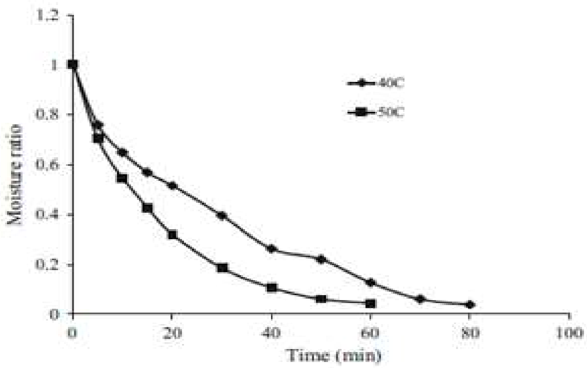
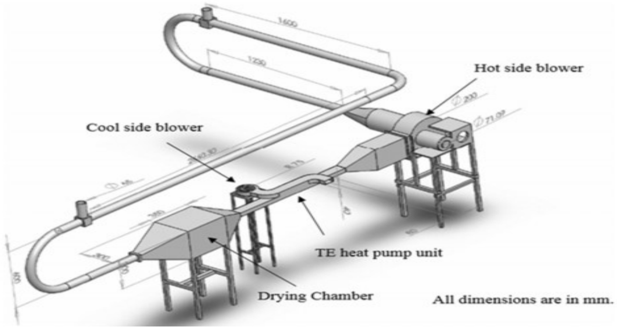


Fig. 6 : Moisture ratios of laurel clock vine leaves for selected drying air temperatures



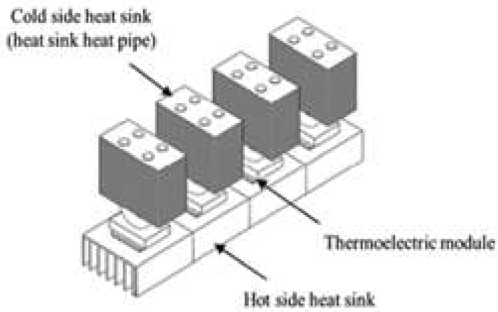


Fig. 7: Schematic diagram of the TE drying system and TE modules arrangement with rectangular fin heat sinks and heat-pipe heat sink

Calculated COP for the entire TE heat-pump drying system was 1.28 and 0.81 for drying-air temperatures of 50 and 40 °C, respectively.

Cold Storage

India wastes up to 16 per cent of its agricultural produce; fruits and vegetables. The country wastes a significant portion of its farm produce due to a weak cold chain infrastructure. The existing cold chain has major impact on global warming. Therefore, the eco-friendly, smaller refrigeration systems which can be operated independent of the electrical grid are to be developed. Namdev *et al.,* 2017, stated that the thermoelectric refrigeration system is new alternative for commercial refrigeration system which has the merits of being light, reliable, noiseless, rugged, and low cost in mass production, uses electrons rather than refrigerant as a heat carrier and is feasible for outdoor purposes in cooperation with solar photovoltaic (PV) cells, in spite of the fact that its coefficient of performance is not as high as for a vapor compression cycle. For small and marginal farmers, the thermoelectric cold storage is advantageous to store products for shorter period and sell it without deterioration of the product.

Distillation Unit

Al-Madhhachi and Min, 2017 designed and constructed thermoelectric distillation system for production of drinkable water. The unique design of this system is to use the heat from hot side of the thermoelectric module for water evaporation and the cold side for vapor condensation simultaneously (Fig. 8). The results of experiments showed that the average water production is 28.5 mL/h with a specific energy consumption of 0.00114 kW h/mL.

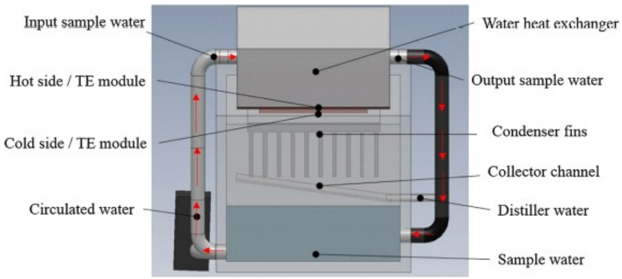


Fig. 8 : Cross-sectional view of thermoelectric distillation system and water recirculation route

Al-Madhhachi & Min, 2017 and Hungerford, 2016 stated that both electrical and thermal energy can be produced by the same solid state module by changing the supply of energy (electricity supply produces thermal energy and thermal energy supply produce electrical energy) to the module. The quick change in the polarity of the module result the hot side *gets* cold and cold side gets hot. Getting both energies form the same module is the great advantage of solid state modules. According to Jaziri *et al.,* 2019 the quick change in the polarity of the modules will results in short life of the module. This is the major problem of the modules. But the change in polarity of the module will actually shorten the life of module. Further research has to be carried out on this aspect to overcome this problem in future days.

Liquid Cooler

Zhao and Tan 2014, conducted the research on the potential use of TEC modules, the basic material of TEC, modelling and application for small-scale cooling.

Aziz *et al.,* 2017, developed portable beverage cooler using one stage thermoelectric cooler module which yield cooling room temperature until 15 °C in 30 min operation by consuming 20 W of electricity. Suryawanshi *et al.,* 2016 developed thermoelectric refrigerator for liquid cooling. due to low COP of developed cooling module restricted to small capacity system. For no load condition the system took 4 min to reduce the temperature by 11 °C. For load condition it took 21 min to reduce the temperature by 8 °C. Thermoelectric liquid cooler can maintain the temperature of liquids (Milk and dairy products, beverages, water etc.) lower than the surrounding atmosphere temperature.

According to the Khodegaonkar *et al.,* 2019 the use of heat sinks and exhaust fans at the hot side of the module to dissipate the heat to get effective cooling and it will increase the performance of the cooling module. Al-Madhhachi and Min, 2017 stated that the use of the both energies simultaneously (cold and heat) will increases the performance of the module (COP). The use of heat sink at hot side will increase the output of cold but the use of the both energies simultaneously (like distillation unit) increases the COP of the solid state module. In next upcoming days the more research has to be done on use of both energies simultaneously in food and agriculture sector. For example, use of cold for precooling and hot side for the blanching of food products in food processing sectors.

Scope of Solid State Cooling and Future Line of Work

1. Dairy farming is a class of agriculture for long-term production of milk, which is processed either on the farm or at a dairy plant. Milk spoilage is the major problem in the rural areas of India due to lack of refrigeration facilities. The solid state cooling module can be used as milk cooling portable device to avoid milk spoilage at farm level
2. Solid state modules can also be used as a heat exchanger in food industry
3. Solid state has the capacity of instant cooling and heating, so it can be used for precooling and blanching of food products in food processing
4. Greenhouses require different temperature conditions in different seasons (winter and summer) this requirement can be solved by using solid state modules
5. In greenhouses the one energy of solid state modules is used based on the climate whereas, another energy will be discharged through the exhaust fans to control the surrounding temperature. The discharging heat energy from module can used for producing electricity to run small electrical device like WSN and exhaust fans in greenhouses in summer.

6) Performance of solid state cooling module by using new generation heat transfer fluids like nono fluids, glycol *etc.* can be adopted
7) Increase of COP by utilizing both hot and cold side energy of Peltier module
8) Water circulation for rejection of heat/cold from the other side of module will give better results compared to air circulation
9) The hot side of the module can be used to produce electricity while the cold side is used for cooling purpose. Connecting one more Peltier module to hot side of the other module will produce the small amount of electricity (Seebeck effect) instead of wasting the energy.

In the article, the investigation on thermoelectric module technologies and applicationsis thoroughly reviewed. From the review of the pertinent literature presented above, it can be inferred that thermoelectric technology using different modules used for cooling as well as heating application has considerable attention. The thermoelectric cooling and heating has major advantages over conventional refrigeration system like; TE module works electrically without any moving parts so they are virtually maintenance free, the overall thermoelectric cooling system is much smaller and lighter than a comparable mechanical system, thermoelectric coolers will either heat or cool depending upon the polarity of the applied DC power. This feature eliminates the necessity of providing separate heating and cooling functions within a given system, with an appropriate closed-loop temperature control circuit, TE coolers can control temperatures to better than +/- 0.1°C, when used 'in reverse' by applying a temperature differential across the faces of a TE cooler, it is possible to generate a small amount of DC power. Thermoelectric devices do not use or generate gases of any kind, therefore modules are environmentally friendly. But is has the drawback of low performance (COP) compared to the conventional cooling systems. Many researchers try to improve the COP of the thermoelectric modules using different material. Thermoelectric coolers to be practical and competitive with more traditional forms of technology, the thermoelectric devices must reach a comparable level of efficiency at converting between thermal and electric energy.

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