

DESIGN AND FABRICATION OF PORTABLE THERMOELECTRIC VACCINE PRESERVATOR

Sujith G¹, Sarath Raj²

¹Assistant Professor, sujithgu@gmail.com

²Assistant Professor, srsnit2013@gmail.com

Department of Mechanical Engineering, SNIT, Adoor, India.

Abstract

The objective of this project work is to develop portable thermoelectric refrigeration system capable of maintaining vaccine temperatures between 8 °C and 13 °C. The main system consisted of thermoelectric module as cooling generator along with insulated cabin, battery and charging unit. Thermoelectric elements perform the same cooling function as Freon-based vapor compression or absorption refrigerators. To ensure the success of this project several criteria's are to be satisfied such as portability, size and cost of the system. The design of the preservator is based on the principles of thermoelectric module (i.e., Peltier effect) to create a hot side and a cold side. The cold side of the thermoelectric module is used for refrigeration purposes; provide cooling to the vaccine chamber. On the other hand, the heat from the hot side of the module is rejected to the surroundings with the help of heat sinks and fans. After gathering experimental data's and necessary guidelines from research papers on the thermoelectric refrigeration systems, the initial design of the model was made. Based on the heat load calculations, the thermoelectric module is selected. The system was fabricated and was experimentally tested for the cooling purpose. The capability of the system to maintain the required temperature and the time for reaching the same were analyzed. The results showed that the system can maintain the vaccine storage temperature at 8°C and 13 °C under ambient temperature up to 30 °C with minimum power consumption of 34 Watt. The proposed thermoelectric module, to maintain the vaccine storage temperature, satisfied the design criteria. Coefficient of performance of the vaccine preservation (COP_R) was calculated and found to be about 0.106.

Keywords: Thermoelectric module, Seebeck Effect, Peltier Effect

1. Introduction

In 2002, an estimated 2.1 million people around the world died of diseases that were preventable by widely available vaccines. This toll included 1.4 million under the age of five. Among these deaths, over 500,000 were caused by measles; nearly 400,000 by hemophilic influenza; nearly 300,000 by pertussis; and 180,000 by neonatal tetanus. Moreover, in 2003, around 27 million children worldwide were not reached by the vaccines, including 9.9 million in South Asia and 9.6 million in sub-Saharan Africa. Those who missed out on routine vaccination programs tended to be people living in remote areas, urban slums and border areas. They also included indigenous groups, displaced populations, and people lacking access to vaccination (WHO1, 2005). One of the most important barriers to effective vaccination programs in remote areas is the spoilage of vaccines, even before their arriving at the remote locations for the end users. Vaccine chamber and handling practice deficiencies have been a serious on-going problem. (Woodyard et al, 1995 and Bishai et al., 1992). It has been reported that about 50 % of transported vaccines are thus wasted. (Sabeena, et al., 2002). In a remote Colorado County, about 93% of vaccine refrigerators were found to have temperatures outside the acceptable range (Woodyard et al., 1995). Unreliable access to electrical power in remote

areas is a barrier to maintaining potency of vaccine products. Approximately 1.6 billion people today do not have access to electricity, and four out of five people having unavailability of electricity live in rural areas (Birol, 2002). The most common cooling system utilized for cooling vaccines at health posts is with the vapour compression refrigerator and cold boxes. The vapour compression system employs mechanical pumps to actuate the compression and the subsequent expansion of specific working fluids. The advantage of this system is that it is capable of refrigerating large loads with high efficiency. However, the system is heavy due to the compressor, is costly and noisy during operations. Thus, the system is not suitable or readily portable to remote areas. Alternatively, the cold box (vaccine carrier), which weighs and costs less, simply uses an ice pack to cool the vaccines. It is much less reliable, and offers cooling over a relatively short duration. Another alternative cooling technology which is becoming increasingly popular and attractive to the portable cooling application is thermoelectric modules. The modules are made of semiconductor materials electrically connected in series configuration and thermally in parallel to create cold and hot surfaces. Although they are less efficient than the vapour compression system, they are very light, low in cost, silent in operation, and are environmentally friendly. In this project work, the thermoelectric module was utilized for cooling. The objective of this present work is to develop a workable portable thermoelectric cooling system with a capacity of 4 liters of vaccine chamber, with the temperature maintained between $+10^{\circ}\text{C}$ to $+12^{\circ}\text{C}$. It will be used in remote locations in the world where there is no grid electricity, and where electrical power supply is unreliable.

2. Literature survey

Review of a number of patented thermoelectric refrigerator designs, a photovoltaic-direct/indirect thermoelectric cooling system, and research studies from the literature are described in the following section. A simple design was proposed by Beitner (1978) consisting of thermoelectric modules directly powered by an external DC source and an external thermal sink to dissipate heat to ambient by using natural convection cooling. Reed and Hatcher (1982) proposed an effective way to enhance the heat dissipation at the hot end of thermoelectric modules by using the cooling fan. Park (1996) introduced a new design of thermoelectric refrigerator by combining the benefits of super insulation materials and phase change materials to impart an environmentally benign system that was energy efficient and could maintain relatively uniform temperature for the extended periods of time with relatively low electrical power requirements. Gillery and Tex (1999) proposed the design of a thermoelectric refrigerator by employing evaporating/condensing heat exchanger to improve heat dissipation at hot end of thermoelectric modules. Guo et al. (2002) proposed a new approach to dissipate heat by using heat pipes for heat conducting and dispersing. In the design a multi bundle of the heat pipe conducting plates was installed at the cold end of the thermoelectric devices and the other heat pipe was installed at the hot end of the thermoelectric cooling member with the fin plates or the fin strips. Riffat et al. (2001) experimentally evaluated two thermoelectric refrigeration systems comprising a 67 litre cabinet and six thermoelectric modules (type PT-12-40). The special features of this design are: "heat-pipe embedded fin" heat sink units mounted on the hot side of the thermoelectric modules and an encapsulated phase change material used as cold heat sink in the prototypes. A mixture of sodium sulphate, potassium chloride and ammonium chloride with additives to prevent super-cooling was utilized in an encapsulated PCM with a transition temperature point of 7°C . The experimental results showed that utilization of an encapsulated phase change material was found to improve the COP of the thermoelectric refrigeration system and a heat pipe-embedded fin could highly transfer the heat from the hot end of TEM with thermal resistance of $0.012^{\circ}\text{C}/\text{W}$ and heat capacity of 150 W at vertical position. Omer et al. (2001) improved the performance of thermoelectric refrigerator of Riffat et al (2001) by integrating a thermal diode (vertical heat pipe) between the encapsulated phase change material (PCM) and the cold side of thermoelectric modules. The experimental results showed that the COP of the system could be improved by utilization of PCM at the cold side of thermoelectric modules and the thermal diodes was also feasible to prevent heat leakage to the PCM in the event of the power being turned off. Guler and Ahiska (2002) experimentally tested a portable thermoelectric medical cooling kit consisting of thermoelectric module, cooling fan, and fin. In addition, Microcontrollers LM 35DZ and 89LV52 were employed in this system for temperature sensor and temperature controller, respectively.

3. Thermoelectric refrigeration

A voltage difference is produced when two wires of different materials are joined together at its end and heated at one end, this phenomenon was discovered by Thomas Seebeck in 1821 and is known as the Seebeck Effect. The two main applications of Seebeck effect include temperature measurement and power generation.

Fig 3.1: Seebeck effect: two wires of different metals are connected to a closed circuit. If one end is heated a current will flow continuously. Thirteen years later Jean Charles Anthonise reversed the flow of electrons in Seebeck’s circuit to create refrigerating effect. This phenomenon is known as “Peltier Effect”. This idea forms the basis for the thermoelectric refrigerator.

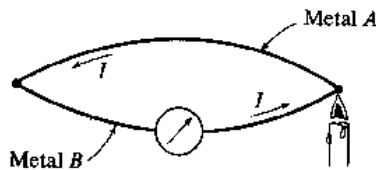


Fig. 3.1 Seebeck Effect

In 1854, Scottish scientist William Thomson (later Lord Kelvin) discovered that if a temperature difference exists between any two points of a conductor carrying current, heat is either evolved or absorbed depending upon the material. If such a circuit absorbs heat, then on reversing the direction of the current or the temperature gradient heat may be evolved.

4. Thermoelectric cooling modules

Although thermoelectric effect was discovered more than 150 years ago, thermoelectric devices (TE modules) have only been introduced commercially during recent decades. For some time, commercial TEs have been developing in parallel with two mainstreams of technical progress – electronics and photonics, particularly optoelectronics and laser techniques. Lately, a substantial increase in the application and use of TE solutions in optoelectronic devices has been observed, such as diode lasers, photo detectors, solid- state pumped lasers, charge-coupled devices (CCDs) and others. The progress in applications is due to the following advantages – they are solid state, have no moving parts and are miniature, highly reliable and are flexible in their design to meet particular requirements.

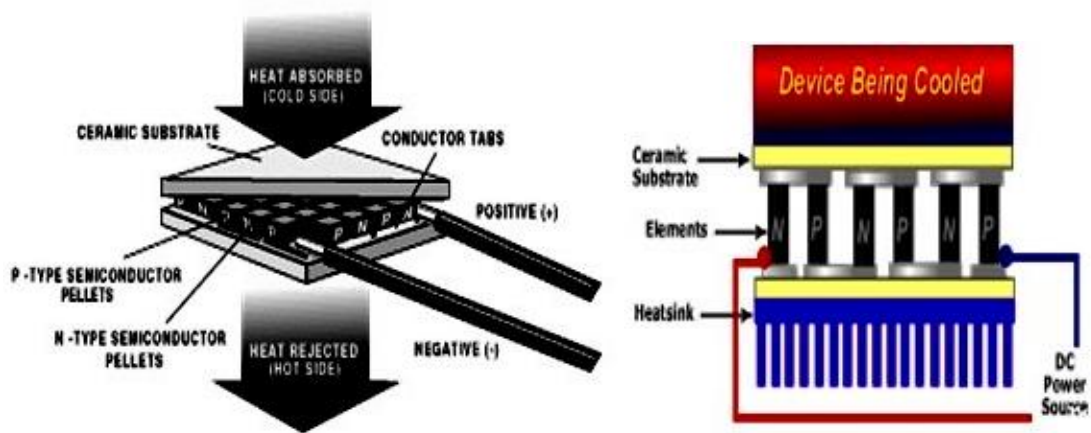


Fig. 4.1 Thermoelectric module assembly

4.1 Theory

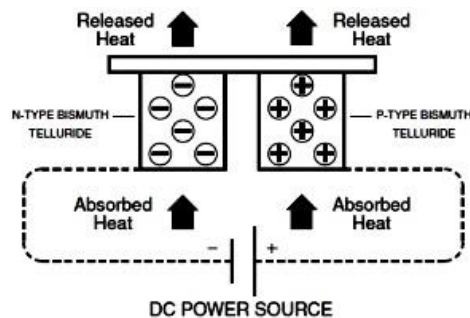


Fig 4.2: Module working.

When a DC voltage is applied to the module, the positive and negative charge carriers in the pellet array absorb heat energy from one substrate surface and reject it to the other substrate at the opposite side. The surface where heat energy is absorbed becomes cold; the other surface where heat energy is released becomes hot. Reversing the polarity will result in reversed hot and cold sides.

The Peltier effect can be described by the Peltier coefficient, Π , which is a measure of the energy carried per unit charge and is relatively large in semiconductors. The Peltier effect between two metals is quite small. This is due to the fact that the conduction electrons in a metal have energies very close to the Fermi energy, which is the highest energy level, occupied by the electrons at absolute zero. Thus to better understand the Peltier coefficient a semiconductor will be considered since semiconductors tend to have relatively high Peltier coefficients.

The common way of presenting the Peltier coefficient is the following:

$$P = S \cdot T$$

Here 'S' is the Seebeck coefficient defined by contacting materials, their properties and temperature. T is the junction temperature in Kelvin.

4.2 Characteristics of Good Thermoelectric Materials

A good thermoelectric material should possess three essential qualities. Firstly, the Seebeck coefficient, S , should be large. Secondly, the electrical conductivity should be high which means that heat loss is minimized. Lastly, the thermal conductivity should be low which minimizes heat lost by heat conduction. A measure of the thermoelectric quality of a material is the figure of merit. Usually the figure of merit is multiplied by temperature to give the dimensionless figure of merit, ZT . Good values of the dimensionless figure of merit should be around unity.

In order for a thermoelectric material to be competitive commercially, the dimensionless figure of merit must be at least 3. At first; metals and metallic alloys were believed to be good thermoelectric materials. However, ZT values for metals tend to be very small. This is due to the fact that metals roughly have the same thermal conductivity to electrical conductivity ratio for a given temperature, which is given by the Wiedemann-Franz law: This is because in a metal the thermal and electrical currents are carried by the conduction electrons. The high Seebeck coefficient that is consequently needed to make ZT of the order of unity is too high to be possible theoretically or experimentally. The

next type of materials considered were semiconductors, which can have very high Seebeck coefficients. However, semiconductors with high Seebeck coefficients often times have very small electrical conductivity thus making the search for a good thermoelectric material that more difficult. However, using doped semiconductors results in improvements in the value of ZT. Also, studies have shown that a good thermoelectric material is likely to be formed from elements of high atomic weight, or compounds made of heavy elements. Good examples of thermoelectric materials made from elements of high atomic weight are based on the compound bismuth telluride Bi_2Te_3 , which are commonly used, for example, in thermoelectric refrigerators.

4.3 Thermoelectric module construction

A TE module consists of thermoelectric couples (n and p type semiconductor legs) that are connected electrically in series and thermally in parallel configuration and are soldered together, sandwiched between two ceramic plates. The latter form the hot and cold side of the thermoelectric cooler (TEC). The configuration of TE modules is shown in figure 4.1

Commonly, a TE module consists of the following parts.

- **Regular matrix of Thermo Electric elements – pellets.** Usually, the semiconductor materials such as bismuth telluride, antimony telluride or their solid solutions are commonly used. The semiconductors are the best materials to be used due to a complex optimal TE performance and technological properties.
- **Ceramic plates** –The plates provide mechanical integrity of a TE module. They must provide good electrical insulation from the object to be cooled and the heat sink. The plates must have good thermal conductance. The aluminium oxide (Al_2O_3) ceramics are most widely used due to the optimal cost to performance ratio and developed processing technique. Other ceramics, such as aluminium nitride and beryllium oxide are also used.
- **Electric conductors** – They provide electric contacting of pellets and contacts to leading wires. For most of the low-power modules, the conductors are made as thin films and multilayer structure containing copper (Cu) as a conductor, deposited onto ceramic plates. The high-power modules are made from Cu tabs in order to reduce resistance.
- **Solders** - The solders used include antimony-tin and lead-tin alloys. The solders provide good assembling of the module. The melting point of a solder is one of the limiting factor of operating temperature of the module. For better life of the module, operation temperature must be well below the melting point of the solder material.
- **Leading wires** – They are connected to the ending conductors to deliver power from a direct current (DC) electrical source.

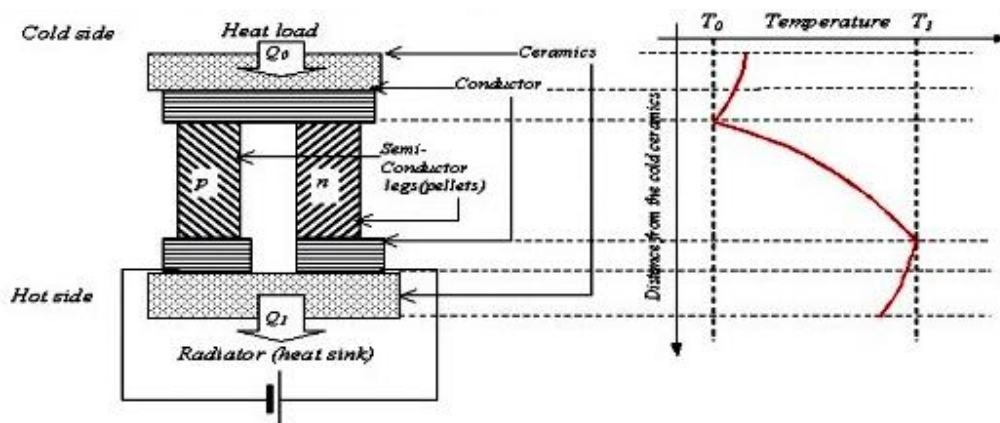
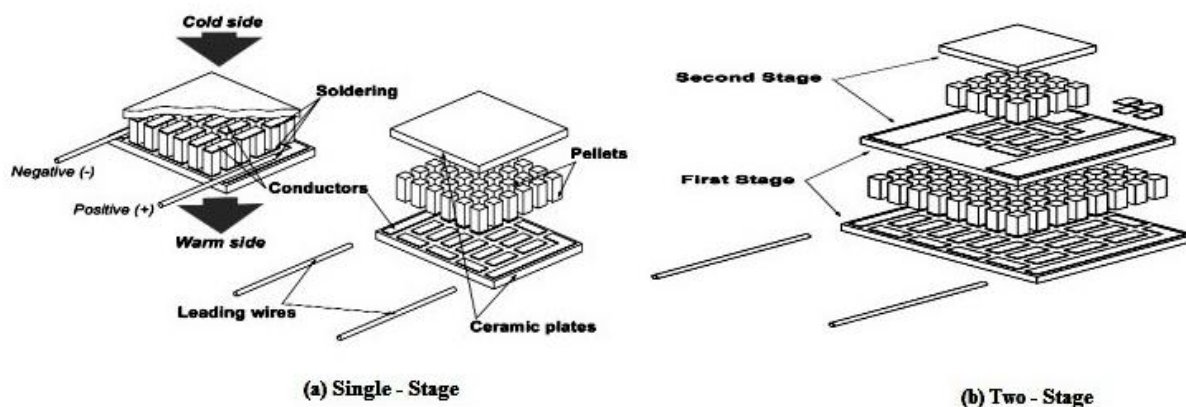


Fig. 4.3 Simplified Scheme of TE Module and the Temperature profile.

A single-stage module consists of only one matrix of pellets and a pair of cold and warm sides (see figures). A multi-stage module can be viewed as two or more single stages stacked on top of each other. The construction of a multi-stage module is usually of a pyramidal type and each of the lower stage is bigger than the upper stage. Once the top stage is used for cooling the lower stage requires higher cooling capacity to pump heat that is dissipated from the upper stage.

**Fig. 4.4 Module Construction**

5. Design of thermo electric vaccine preservator

5.1 Project Objectives.

In this proposed work, the main aim is to develop a portable refrigeration system with a capacity of 4 litres of vaccine chamber. The system should be capable of maintaining the temperature of the vaccines between $+2^{\circ}\text{C}$ and $+12^{\circ}\text{C}$ range for a long time. Since the system has to be used in remote areas where power is scarce, alternative sources of energy like battery or solar power has to be incorporated in the design. Since the system has to be portable, it should be compact as well as light. Moreover the system is meant for outdoor use which makes better insulation and radiation control mandatory. In order to meet worse scenario, even though the system is to designed for maintaining a fixed chamber temperature throughout the operational period, the design should be such that it can adaptable for refrigerating the chamber from ambient temperature to the required temperature.

5.2 Proposed Model

With the constraints imposed by the objectives a double walled rectangular box with an insulation sandwiched between the walls as shown in fig 6.1 was proposed.

5.2.1 Geometry

It constitute doubled walled cabin with insulation having the following dimensions

Top and bottom panel dimensions = $0.13 \times 0.27\text{m}$

Vertical side panel dimension = $0.27 \times 0.13\text{m}$

Front and back panel dimensions = 0.13x0.13 m

5.2.2 Materials

Mild steel sheets with thermal conductivity of 42W/mK were used
Expanded polystyrene (EPS) slabs with 20 mm thickness having a density of 30kg/m³ and thermal conductivity of 0.033W/mk were used to give the required thermal insulation.

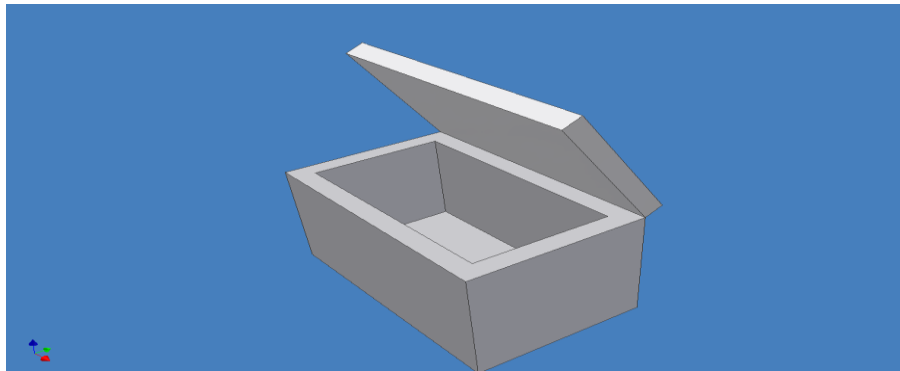


Fig 5.1: The proposed double walled cabin

5.3 Design Procedure

In the design of a thermoelectric (TE) cooling system, one of the most important processes is reaching an understanding of the thermal load. With this vital information, we can wisely choose the best TE device or heat exchangers for the purpose. Each thermoelectric system has a unique capacity for moving heat. Our design is based on how much heat must be removed from the thermal load to achieve the performance objectives. Once the module is selected, fin design is done based on the amount of heat that has to be removed.

6. Fabrication and assembling

6.1 Fabrication of the Cabin

Cabin Walls- The rectangular double walled cabin is made using Mild steel sheets of 1mm thickness. The Designed dimension (27mm x 15mm x 13mm), of the cabin is obtained by performing suitable bending operations on the MS sheet. To give better surface finish the sides are welded together. The top door panel of the cabin is fastened using spot welding. Rubber beading is given to prevent the heat leakage, through the sides of the top door panel. To prevent radiation heat transfer and to give better surface finish, the outside of the cabin is coated with aluminium paint.

Insulation- Expanded polystyrene foams are made by mixing the polystyrene with a solvent, adding a gas under pressure and finally the mixture is extruded to produce the required thickness. The extrusion process improves the characteristics of the final foam, i.e. its mechanical resistance increases, producing non-interconnecting pores and a more homogeneous material. The value of mechanical resistance of expanded polystyrene foams can vary from 0.4 to

1.1 kg/cm². There are several grades of foams available with their densities vary from 10 to 33 kg/m³, with thermal conductivities that are lower with the increase in density.

EPS slabs with 20 mm thickness having a density of 30kg/m³ were used to give the required thermal insulation. The slabs having a thermal conductivity of 0.033 W/mk, were pasted to the inside walls of the cabin using a mixture of MDI (methyl-di-isocyanides) and castor oil.

6.2 Assembling

The thermoelectric module has to be mounted on aluminium plate on cold side and fin on the hot side with a thermal interface material in between. Once the module is mounted it can be assembled to the cabin

6.2.1 Mounting of Thermoelectric Module

Mounting of module has to be done with utter most care. It is mounted in the following steps.

- 1) The surface of the fin, to be attached to the Peltier Module is wiped free off dirt and grease using alcohol or similar and thin film of thermally conductive silicon grease on the suitable surfaces.
- 2) In the same way, heat emitting side of the Peltier Module is wiped with alcohol or similar and thinly spread with thermally-conductive silicon grease.

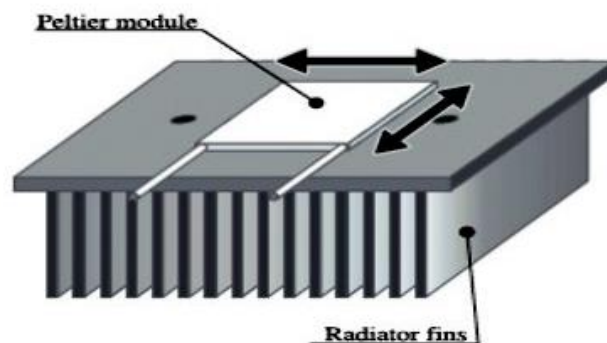


Fig 6.1: Installing the peltier module

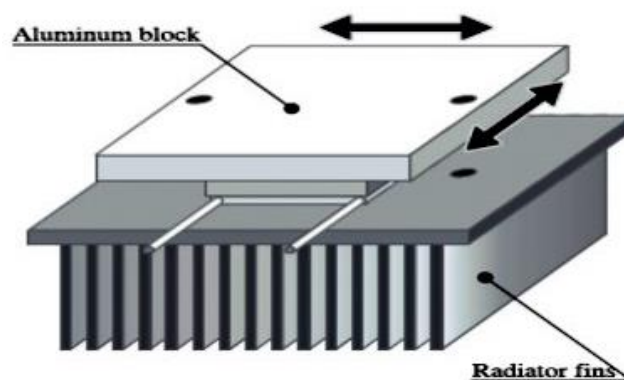


Fig 6.2: Installing the aluminium block

- 3) The heat-emitting side of the Peltier Module is placed onto the appropriate place on the radiator fins, taking care that while applying light pressure to the unit, slide the unit back and forth, left and right, approximately 20 times to ensure a perfect fit and to lose any layer of air between the connecting sides.
- 4) As heat absorbing side of the Peltier Module is made free of dirt and grease, in the same way, the surface of the aluminium block is wiped to attached to the Peltier Module with alcohol or similar and thinly applies thermally-conductive silicon grease.
- 5) The aluminium block is placed onto the heat absorbing side of the Peltier Module. Then once again, apply light pressure to the block and gently slide it back and forth, then left and right, to ensure a tight fit and remove any layer of air between the connecting sides.
- 6) The screws are tightened until the washers are properly held in place. While doing so, to ensure that even force is applied across the module, apply 200 ~ 300 N (for a 30 mm square unit) of pressure to the centre of the aluminium block and tighten each of the screws alternatively little by little.

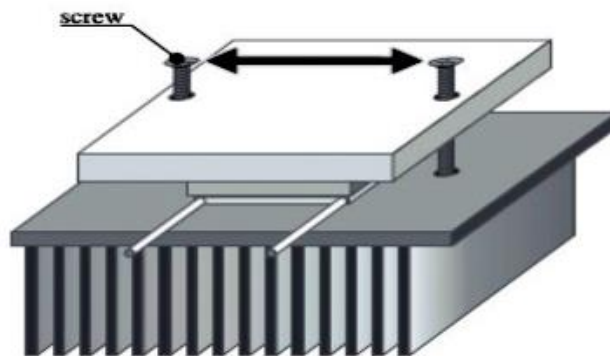


Fig 6.3: Order of screw tightening

- 7) When the module is gently secured, tighten the screws alternately in the same manner as in step 8 to a torque of 10 Nm. Continue tightening to a final torque of 20 ~ 30 Nm.
- 8) As a protection against humidity, seal the perimeter of the TE Module with a silicon sealant or similar and allow to dry for the requisite time.

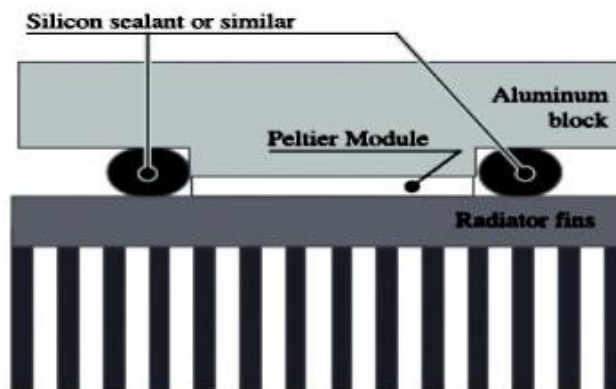


Fig 6.4: Humidity protection for the Peltier module perimeter.

6.2.2 Assembling Module Unit with Cabin

Once the TE module has been mounted, it is ready to be installed on to the insulated double walled cabin. The module assembly is integrated into the cabin with the help of fastening screws. The cold plate (Al) should be concurrent with the inner wall and the fin is exposed to outside. In order to enhance the cooling rate screws are extended up to the inside cabin space. The lateral side and all other exposed sides of the module assembly are insulated. So as to augment the convective heat transfer through the fins, cooling fans are provided. Provisions are provided on the outer shielding cover for mounding the cooling fan. The shield cover also includes the control panel and the power input socket.

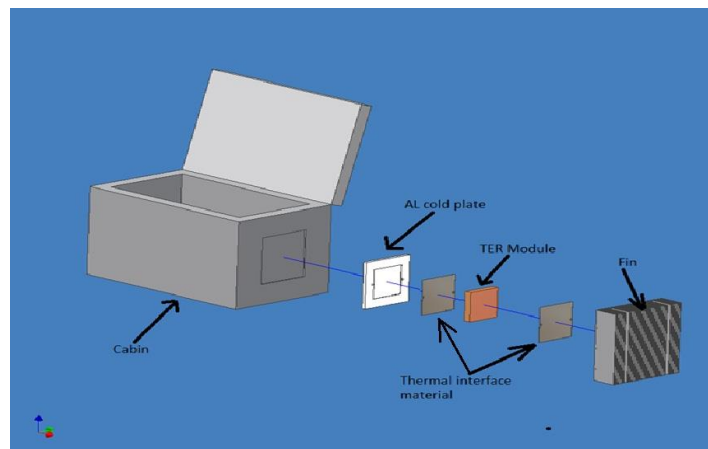


Fig 6.5: The 'exploded view' of assembly of the TER.

The associated components includes,

- Battery charging unit
- 12 V DC batteries etc.

6.3 Fabricated Model



Fig 6.6: Fabricated model of the Thermoelectric Vaccine Preservator with battery attached.

7. Experimental Investigations

Analysis of the experimental setup and performance evaluation was done; the temperatures of the cold side of the thermoelectric module were measured by thermocouple wire which was connected to the side of the module. The hot side of the thermoelectric module was made to contact with the heat sink whereas the cold side of the thermoelectric module was used to cool the refrigerator cabinet. In order to validate the performance of the system two experiments were conducted on the system.

7.1 Performance test

In order to ensure that the system satisfies the design requirement of maintaining a fixed temperature, test were conducted with initial temperature of load at required temperature. Water at 10 °C is filled in the cabin before the system is switched ON. Readings were taken every 15min until steady temperature was obtained.

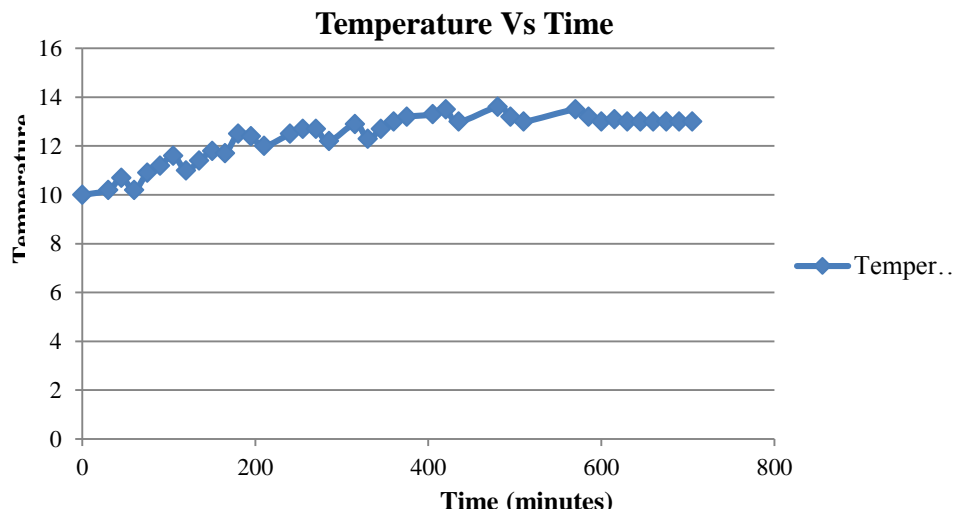


Fig 7.1: temperature vs. time graph (performance curve).

The results show that, the heat in leak rate was greater than heat removal rate at lower temperatures. But at temperature of about 13 °C the heat in leak and heat removal was balanced, as a result the plot is parallel to time axis. Heat in-leak through the insulation exceeded the anticipated design value. Lower temperatures can be maintained by making apt changes to the insulation.

7.2 Cool down test

For analysing the performance of system water load is considered. Water at 26.6°C was filled in the container before switching ON the system. The temperature reading is taken out at every 30 minute interval and was tabulated. The readings were repeated until we get the least possible steady temperature.

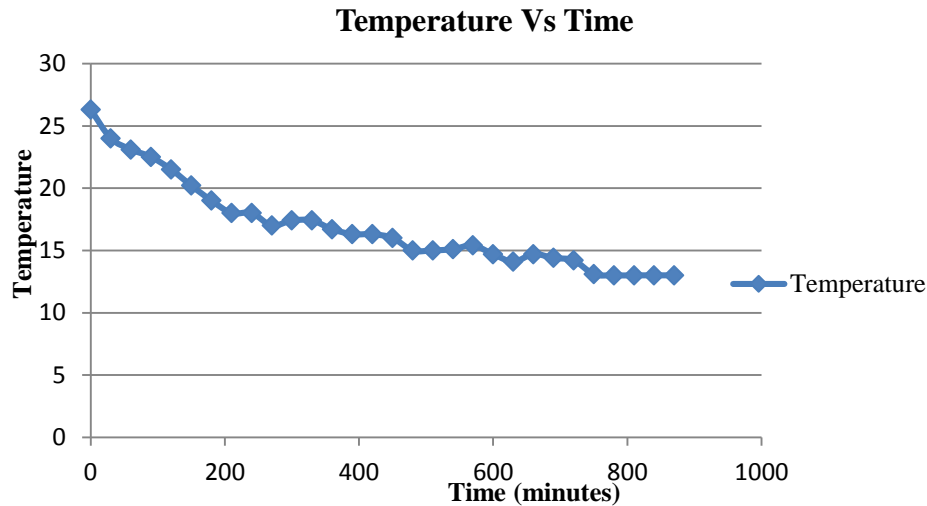


Fig 7.2: temperature vs. time graph (cool down curve)

Even though the system is mainly designed for maintaining a fixed temperature, the above experiment was conducted to ensure that the system can be adapted for sensible cooling also. The steady temperature attained was 13°C. It took almost thirteen hours to attain the same from ambient conditions. The cabin temperature drop was at an average rate of 1.06°C/hr.

7.3 Performance of the thermoelectric refrigerator

When the designed thermoelectric refrigerator was tested, it was found that the inner temperature of the refrigeration area was reduced from 26.3 °C to 13 °C in around 750min. Coefficient of performance of the refrigerator (COP_R) was calculated. Properties of water is used in place of vaccine for calculation .In these calculations, the properties of water are (density = 1 kg/L and C = 4.18 kJ/kg).V = 3.0 L. Calculate COP_R:

$$COP_R = \frac{Q_{cooling}}{W_{in}}$$

$$M = \rho V$$

$$= 1 \text{ (Kg/L)} \cdot 3.0 \text{ (L)}$$

$$= 3.0 \text{ Kg}$$

$$Q_{cooling} = mC\Delta T$$

$$= 3.0 \times 4180 \times (26.3 - 13)$$

$$= 166782 \text{ J}$$

$$Q_{cooling} = \frac{Q_{cooling}}{\Delta t}$$

$$= \frac{166782}{750 \times 60}$$

$$= 3.706 \text{ W}$$

$$W_{in} = VI + \text{Fan input}$$

$$= 2.5 \times 12 + 4$$

$$= 34 \text{ J}$$

$$\begin{aligned} \text{COP}_R &= 3.706/34 \\ &= 0.109 \end{aligned}$$

8. Conclusion

We have been successful in designing a system that fulfils the proposed goals. However we do realize the limitations of this system. The present design can be used only for maintaining a particular temperature. The system is unable to handle fluctuations in load. Extensive modifications need to be incorporated before it can be released for efficient field use. Thermoelectric refrigeration is one of the key areas where researchers have a keen interest. Some of the recent advancements in the area surpass some of the inherent demerits like adverse COP. Cascaded module architecture has defined new limits for its application. Moreover recent breakthrough in organic molecules as a thermoelectric material promises a bright future for TER. With more and more countries showing interest in Montreal and Kyoto protocol, TER is gaining more attention as an affordable, reliable and a green refrigeration alternative.

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Author Biography

SUJITH G – Completed M.Tech in Industrial Refrigeration and Cryogenic Engineering from TKM College of Engineering, Kollam and B.Tech from Saintgits College of Engineering, Kottayam. Area of interest is in “Heat Transfer and Fluid Flow Analysis”.

SARATH RAJ – Completed M.Tech in Industrial Refrigeration and Cryogenic Engineering from TKM College of Engineering, Kollam and B.Tech from Travancore Engineering College, Kollam. Research interests include 1. Refrigeration and Cryogenics. 2) Combustion studies in rocket fuels.3) Cooling systems in rockets.4) Automobile Engineering.