

DISSERTATION

on

Thermoelectric Module Application for Deep Freezing

*Submitted in partial fulfilment of the requirement for the award of degree
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Master of Engineering

in

CAD/CAM Engineering

Submitted by

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DECLARATION

I hereby declare that the work done in thesis report entitled, “ *Thermoelectric Module application for deep freezing*” submitted towards partial fulfilment of award of Master of Engineering degree in *CAD/CAM Engineering in Mechanical Engineering Department of Thapar Institute of Engineering and Technology, Patiala* is an authentic record of work carried out by me at *LG Soft, Greater Noida*, under the supervision and guidance of *Dr. Tarun Kumar Bera, Associate Professor, Thapar Institute of Engineering and Technology, Patiala* and *Mr. Rajat Goyal, Deputy Manager, LG Soft India Private Limited, Greater Noida*.

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This is to certify that above declaration made by the student concerned is correct to the best of my knowledge and belief.



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Acknowledgement

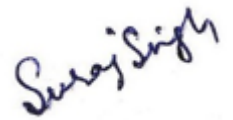
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Suraj Singh

Abstract

With the increasing demand of having a lower temperature in the freezer than the existing, home appliance companies are doing continuous research to come up with a product that has the capability of achieving such a desired lower temperature, say -50°C . Such a lower temperature is desired because the ice forming time of most of the commercial refrigerator is 90 min to 120 min and also due to the fact that few stuffs required to be stored at considerably lower temperature, whereas the existing capability of freezer in the refrigerator is -25°C . Also, due to continuous or periodic opening of freezer, the temperature drops with every opening and therefore, stabilisation of that temperature will again take some time. Therefore, if there would be a separate compartment or box in the freezer that can withstand such a desired lower temperature, then an isolated box in the freezer can be made which would be practically isolated from the rest of the freezer. By having a temperature of -50°C , the ice making time will be reduced to 30 min. Commercially available refrigerators with inbuilt ice-makers have the problem of its size and the space that it utilizes. Apart from that, an ice maker is capable of making ice only and nothing can be stored in an ice maker, whereas a deep freezer can store things apart from making ice. Also, extra amount of refrigerant is needed to be added to the system for the working of ice maker. The idea presented in this thesis is to make a separate zone in the freezer that has the capability of achieving a temperature of -50°C along with a temperature difference of 50 or more without using any refrigerant or traditional refrigeration cycle. To achieve this deep freezer temperature, thermoelectric or peltier modules are used and a prototype for deep freezer is fabricated. The heat load required to be handled for making ice in 30 min is calculated and correspondingly a module selection is carried out on the basis of such heat load. Performance analysis of the module is done and several modules were selected on the basis of such analysis. After choosing such modules, a series of experimentation was carried out to achieve the desired goal. Cascading of the module was done to save on cost and desired goal was achieved. At the end, future work is suggested to carry out the experimentation by placing the prototype of deep freezer within the freezer of a refrigerator.

Keywords: Deep freezer, Refrigerant, Thermoelectric or peltier module, Prototype, Cascading, Deep freezer temperature

List of Abbreviations

COP	Coefficient of performance
DC	Direct current
EMF	Electromotive Force
RAC	Refrigeration and air condition
TE	Thermoelectric effect
TEC	Thermoelectric couple
TEM	Thermoelectric module

Nomenclature

A	Area over which heat flux is taking place
A_m	Overall module footprint area
A_N	Area of N leg
A_P	Area of P leg
CP	Compression pressure
C_P	Specific heat at constant pressure
d	Bolt size
H	Electrical conductivity
h	Enthalpy
I	Current drawn by the conductor
K	Module's conductance
L_M	Length of module
L	Latent heat
m	Mass of water
n	Number of screws
Q	Amount of heat to be extracted from water
Q_C	Heat pumped by the module
Q_H	Heat liberated on the hot side of the module
Q_{Total}	Total amount of heat to be extracted from water
R	Module's resistance
s	Thermoelectric power
S_E	Seebeck coefficient
S_{ENEW}	Seebeck coefficient of new module configuration
S_P	Seebeck coefficient of P leg
S_N	Seebeck coefficient of N leg
T_C	Cold side temperature
T_H	Hot side temperature
T_m	Mean temperature
T_S	Torque coefficient
Z	Figure of merit
U	Electrical resistivity
A	Thermal conductivity
P	Electrical resistivity
τ	Thomson coefficient

List of Figures

Figure No.	Figure Caption	Page No.
1.1	Expansion through turbine	4
1.2	Expansion through a porous plug	4
1.3	Expansion of saturated liquid 1-2: Isentropic; 1-2': Isenthalpic	5
1.4	Expansion of subcooled liquid 3-4: Isentropic; 3-4': Isenthalpic	5
1.5	T-P thermodynamic coordinates showing the expansion of gas	6
1.6	Isenthalpic lines with inversion curve (locus of inversion points)	7
1.7	Illustrations of peltier and seebeck effect	8
1.8	Setup illustrating magnetic refrigeration	11
1.9	Principle similarity between mechanical refrigerator and thermoelectric cooler	14
1.10	A TE module with a heat sink	14
1.11	Basic physics behind peltier effect	16
2.1	Compact cooler	20
2.2	A peltier based water dispenser	21
2.3	A peltier based beer tender	21
2.4	A minibar	22
2.5	A dehumidifier	22
2.6	Schematic of deep freezer concept	23
3.1	Schematic showing the sequence of screw tightening in circular and rectangular geometry	26
4.1	A single couple thermoelectric refrigerator	33
4.2	Schematic of different phenomenon occur in a peltier module	40
4.3	Schematic showing a freezer at -20°C with a load of 150mL water at 30°C	41
4.4	Elements in thermal resistances	43
4.5	3D model showing the cascaded arrangement of the peltier module	59
5.1	Fan glued directly to the inner sink	63
5.2	Clamping of peltier module with the box with the help of screws and nuts	63
5.3	Time vs Temperature_1	64
5.4	Time vs temperature difference with respect to the hot junction temperature	65
5.5	Time vs temperature difference with respect to the ambient temperature	66
5.6	Duct with fan	67
5.7	Time vs Temperature_2	68

5.8	Time vs temperature difference with respect to the hot junction temperature	69
5.9	Time vs temperature difference with respect to the ambient temperature	70
5.10	Schematic of readily available cascaded peltier module	70
5.11	PC power supply and its specification	71
5.12	Heat sink suggested in place of the previous heat sink used inside the box	72
5.13	Fan used for this experiment	73
5.14	Time vs Temperature_3	73
5.15	Time vs temperature difference with respect to the hot junction temperature	74
5.16	Time vs temperature difference with respect to the ambient temperature	75
5.17	3D printed screws	77
5.18	Instant adhesive used for joining HIPS and 3D printed screws	77
5.19	Figure shows the screw and HIPS pieces joined together	78
5.20	Time vs Temperature_4	78
5.21	Time vs temperature difference	79
5.22	Time vs temperature difference _Change in temperature due to sudden shock on the assembly	80
5.23	Time vs Temperature_5	81
5.24	Time vs temperature difference	82
5.25	Multimeter showing a reading of -19.8°C	82
5.26	Time vs Temperature_6	83
5.27	Time vs temperature difference	84
5.28	Time vs Temperature_7	85
5.29	Breakout of time vs temperature graph for first 10 min	86
5.30	Time vs temperature difference	87
5.31	Frost deposited on the sink	87
5.32	Breakout of time vs temperature difference graph for first 10 min	88
5.33	Time vs Temperature_8	89
5.34	Temperature vs Time till the minimum temperature	90
5.35	Time vs temperature difference	91
5.36	Behavioral reversal of TEM in case of exceeding hot junction temperature	92
5.37	Multimeter showing a reading of -31.6 °C	92
5.38	Front view of the box with insulation	93
5.39	Back view of the box with insulation	93
5.40	Time vs temperature_9	94
5.41	Time vs temperature difference	95

5.42	Frost deposited on the sink	95
5.43	New selected fin	96
5.44	Multimeter showing a reading of -35.5°C	96
6.1	Alpha refrigerator of LG	99
6.2	Freezer compartment of an ALPHA refrigerator	100
6.3	Schematic showing the Deep freezer incorporated with pulmonic valves at the grills	101
6.4	Box placed in the freezer of alpha refrigerator	101
6.5	Perfect match of the box with the space provided in the freezer	102

List of Tables

Table No.	Table Caption	Page No.
4.1	Values of different parameters for the calculation of thermal conductivity	42
4.2	Selected modules for numerical analysis	43
4.3	Performance parameters for module selection	45
4.4	Performance evaluation of TEC1-12706	45
4.5	Performance evaluation of TEC1-12707	46
4.6	Performance evaluation of TEC1-12708	47
4.7	Performance evaluation of TEC1-12710	48
4.8	Performance evaluation of TEC1-12715	49
4.9	Performance evaluation of TEC1-19908	50
4.10	Performance evaluation of TEC1-19911	51
4.11	Performance evaluation of TEC1-19912	52
4.12	Performance evaluation of TEC1-19914	52
4.13	Performance evaluation of TEC1-19916	53
4.14	Performance evaluation of TEC1-24105	54
4.15	Performance evaluation of TEC1-24106	54
4.16	Performance evaluation of MCTE1-12715L-S	55
4.17	Performance evaluation of FERROTEC_72001_127_110B	56
4.18	Performance evaluation of ETC-128-20-08-E	57
4.19	Performance evaluation ET-127-20-15	57
5.1	Experiments conducted for the best module selection	61

Table of Content

Declaration	ii
Acknowledgement	iii
Abstract	iv
List of abbreviations	v
Nomenclature	vi
List of Figures	vii
List of Tables	x
Chapter1: Introduction	1–16
1.1. Background and motivation	2
1.2. Different ways of cooling	2
1.2.1. Sensible cooling by cold medium	3
1.2.2. Endothermic mixing of substance	4
1.2.3. Phase change processes	4
1.2.4. Expansion of liquids	4
1.2.5. Expansion of gases	6
1.2.5.1. Expansion of gases through throttling	6

1.2.5.2. Expansion of gases through turbine	7
1.2.6. Thermoelectric Refrigeration	7
1.2.7. Adiabatic magnetization	11
1.3. Advantages of thermoelectric cooling over the others	12
1.4. Introduction to thermoelectric cooling	13
Chapter 2: Literature Survey	16–23
2.1. Seebeck effect	18
2.2. Peltier effect	19
2.3. Thomson effect	19
2.4. First performance related calculations for thermoelectric devices	19
2.5. First performance evaluation of thermoelectric devices	19
2.6. Semiconductors as Thermoelectric Materials	20
2.7. Thermoelectric applications (1900-1980)	20
2.7.1. First thermoelectric based generator	20
2.8. Thermoelectric application for space	21
2.9. New concepts in Thermoelectricity from 1980-Present	21
2.10. Market survey: Home appliances	21
2.11. Conclusions from literature	23
2.12. Proposed aim	23
Chapter 3: Installation and Reliability of Peltier Module	24–31
3.1. Critical considerations for installation of thermoelectric module	24

3.2. Clamping	24
3.3. Bonding with epoxy	25
3.4. Soldering	28
3.5. Mounting pads and other material	28
3.6. Reliability of thermoelectric module	28
3.6.1. Reliability under high temperature exposure	30
3.6.2. Reliability under thermal cycling	30
3.6.3. Reliability to power cycle	31
Chapter 4: Modeling of Thermoelectric Module	33–58
4.1. Modeling of a thermoelectric couple	33
4.2. Material properties with temperature dependency	36
4.2.1. Seebeck coefficient	37
4.2.2. Electrical resistance of module	38
4.2.3. Thermal conductance of module	38
4.2.4. Expression of parameter in case of a general module	39
4.3. Performance calculation of module	39
4.3.1. Single stage module performance	39
4.4. Numerical analysis of thermoelectric module	41
4.5. Present scenario of freezing ice in freezer	41
4.6. Time reduction in ice making	42
4.7. Calculation of heat influx	42

4.8.	Overall thermal conductivity	43
4.9.	Modules satisfying the requirement	43
4.10.	Important factors to be considered for modules selection	45
4.11.	Calculative analysis of the selected modules	45
4.12.	Conclusion from the numerical analysis of the module	58
Chapter 5: Experimentation		71–96
5.1.	List of experiments	61
5.2.	Experimental results	62
5.2.1.	TEC1-12706 with thermocouple in the box	62
5.2.2.	TEC1-12715 with thermocouple in the box	66
5.2.3.	Cascading (TEC1-12715) -(TEC1-12715) with thermocouple in the box	70
5.2.4.	Cascading (TEC1-12706) - (TEC1-12706) - (TEC1-12715) with thermocouple on the sink	75
5.2.5.	Cascading (TEC1-12706) - (TEC1-12715) - (TEC1-12715) with thermocouple on the sink	80
5.2.6.	Cascading (TEC1-12706) - (TEC1-12706) - (TEC1-12715) with thermocouple on the sink and using cold water on the heat sink side	83
5.2.7.	Cascading (TEC1-12715) - (TEC1-12715) - (TEC1-12715) with thermocouple on the sink	85
5.2.8.	Cascading (TEC1-12715) - (TEC1-12715) - (TEC1-12715) with thermocouple on the sink with cold water on the hot side	88
5.2.9.	Cascading (TEC1-12715) - (TEC1-12715) - (TEC1-12715) with thermocouple on the sink with significant colder water on the hot side	92

Chapter 6: Conclusions and Future Work	97–103
6.1. Installation	97
6.2. Power supply	97
6.3. Temperature difference	97
6.4. Heat sink	97
6.5. Insulation	97
6.6. Module type	98
6.7. Future Work	98
References	103–105

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Thomas Johann Seebeck, a Baltic German Physicist, in 1822, found a relationship between heat and magnetism which was later, in 1823, was named as thermoelectric effect. Seebeck observed that if junction between two different metals or conductors is heated then an electromotive force can be observed. Such an effect can be observed by just joining two dissimilar metals and connecting them with either a galvanometer or voltmeter. Now, if one of the junctions is heated then a fluctuation in galvanometer can be observed. In such an arrangement, these two wires act as a thermocouple. The voltage so achieved is directly proportional to the temperature difference. Thirteen year later in this timeline, a French watchmaker, Jean Charles Athanase Peltier, found that a reverse effect is possible, without knowing the discovery of seebeck. He found that passing electric current between the junctions of dissimilar metals, then a temperature difference will be achieved between these two junctions. Or in other words, one junction will become hotter and other will become cooler. Unlike, seebeck effect, peltier effect is hard to demonstrate, because there is always a heating effect associated with the peltier effect which is due to the current applied between the junctions and this effect is known as joule effect after the name of great mathematician and physicist, James P. Joule. As intuitive, this was realized later by another scientist, William Thomson, also known as Lord Kelvin, that there is an interdependency of the above two, seebeck and peltier, discussed effects. With the help of thermodynamics, he was able to develop a relationship between the coefficients that can describe both peltier and seebeck effect. He also demonstrated that there is a third thermoelectric effect which is known as Thomson effect and exists when an electric current is passed through a conductor having temperature gradient. In such a case, there will either a heat liberation or thermal energy consumption from the environment. After going through the basic understanding of the phenomenon, one may predict that these effects are interfacial effects but in actual they are bulk properties of the conductors involved in these effects. We know that current flow through conductors by means of flow of electrons and these electrons possess different energy levels in different conductors. Therefore, when an electric current is passed across two different conductors then this difference of energies is compensated by heating or cooling effect at the junctions of those dissimilar conductors and the same can be termed as peltier effect. Similarly, when heating is provided, then these electrons will be able to cross the junctions and move to low energy levels and thereby creating an electromotive force and this can be considered as seebeck effect. The process is reversible. It was Thomson who first showed that such phenomenon can be used for generating electricity and also to pump heat from one point to another, or in other words, acting like a heat pump or refrigerator. But such a reversible effect is always accompanied by irreversible effects of conduction and joule effect, therefore, the process becomes inefficient. [Altenkirch, \[2014\]](#) showed the problems with energy conversions. He showed that a thermocouple performance can be enhanced by increasing the seebeck coefficient and to this, the electrical conductivity of the two participating metals or conductors must be increased along with reducing the thermal conductivity. But at that time there was no such possible combination available that can be used for energy conversion because no such arrangement was satisfying the requirement. However, such effects were long used for detection of thermal

radiations and therefore the temperature. It was then in 1950's, when semiconductors were introduced, there was first practical refrigerator based on peltier effect was made. With such an introduction of semiconductors, thermoelectric generators were developed with efficiency good enough for few practical applications. However, there is problem with the advancement of a suitable semiconductor material since it was first introduced. Due to this, not much has been achieved until the end of twentieth century. There are few ideas related to material advancements has been put forward in last decade which are giving good results at laboratory level so far and some reasonable changes in practical application of peltier modules can be expected on the basis of such researches.

1.1 Background and motivation

The conventional refrigeration system that we have been using for more than 100 years is still not capable of giving ice in less than 90 min. However, there are ice makers that are conventional refrigeration system based but then again, they are like a whole separate unit with a complex mechanism along with a heater. Therefore, having such a big unit in refrigerator just for ice is not feasible in cases where the use is not more than as a home appliance. A proper ice maker may be a good option for a commercial use. Also, the only capability of ice maker is making ice only and nothing else. Therefore, if somebody wants to store red meat for longer period or maybe any medicine or other stuff that needs to be kept at very low temperature, somewhere maybe -40°C or -50°C , then that is not possible in any regular or high-end refrigerator these days. Also, at present the freezing time of ice tray of any regular refrigerator is around 90-120 min. Therefore, the wait for getting ice is very huge. Such impossibilities of a regular refrigerator have been a force for researchers to create a separate zone in the existing refrigerator's freezer which can achieve a temperature of -50°C . Such a zone can facilitate storing of anything that may require the respective storage to be at very low temperature or maybe storing ice in less than 30 min.

1.2. Different ways of cooling

Before choosing one specific way of refrigeration or way of achieving a lower temperature, one must have an idea of all available and possible ways of cooling, so as to differentiate between them and choosing the best out of them. There is no doubt in the fact that cooling is more difficult than heating. Even our ancestors were able to achieve heating way before than cooling was first achieved. There is one misconception that refrigeration and cooling are same. Thermodynamically, cooling is a spontaneous process and refrigeration is a non- spontaneous process. Refrigeration needs some external work to be done and more precisely, taking a body's temperature down to what the body is already at and then maintaining it over that state point is what could be a partial definition of refrigeration. In a more non-conceptual way, when a glass of hot water is kept open in the environment, its temperature drops down to that of atmospheric, this is cooling. Now if we place that glass of hot water into the refrigerator then it would achieve a considerably lower temperature than atmosphere and then it can be kept at that lower temperature as long as we want, by keeping it in refrigerator, this is refrigeration. Generally, there could be some part of the system

which may be producing or generating heat which must also be taken care of and this is one important detail which is there in refrigeration.

Now, there are several ways of achieving a lower temperature and some of these ways have been in practice from long decades. Few have found applications in wide range of physical problems whereas other seems to be a lot expensive and sometimes non-reliable in serving. Few famous and important of them are discussed below:

- 1.2.1. Sensible cooling by cold medium
- 1.2.2. Endothermic mixing of substances
- 1.2.3. Phase change processes
- 1.2.4. Expansion of liquids
- 1.2.5. Expansion of gases
 - 1.2.5.1. By throttling
 - 1.2.5.2. Expansion of gases through turbine
- 1.2.6. Thermoelectric refrigeration
- 1.2.7. Adiabatic magnetization

A brief discussion on these is required to have a judgmental insight about them. Following is the discussion of above stated ways of achieving a lower temperature.

1.2.1 Sensible cooling by cold medium

In thermodynamics, the term sensible pertains to cooling/heating without change of phase. Therefore, this way of cooling is done by interaction of the system with a medium which is at lower temperature than the system. This medium could be cold water, brine, air or may be anything else which could serve the purpose. They have some presently alive applications, such as in ice making plants, beverage stores, cooling a building through air and many more. When the medium comes in contact with the system, it takes away heat from the system and that heat is related to that temperature difference which is desired for the system and this heat is given by:

$$Q = mc_p\Delta T \quad (1.1)$$

where Q is the heat extracted from the system, m is the mass of the medium in action with the system, C_p is the specific heat of the medium, and ΔT is the desired temperature difference for the system or the temperature difference experienced by the medium to take the system to the desired state point. It is quite obvious that temperature of the medium would rise during the process and

therefore, an uninterrupted supply of the medium is required which requires a whole setup involving several thermodynamic processes so as to make the cycle efficient.

1.2.2 Endothermic mixing of substance

This can be remembered as one of those school level chemistry class experiment that involved mixing of several salts in water to witness ourselves of an endothermic reaction, that is, a reaction in which heat is absorbed so that cooling is achieved, such experiments can give us a lower temperature of water up to -51°C by mixing of calcium chloride in water. But this method has its own limitation. One of them is recovering of salts and this requires evaporation of water.

1.2.3. Phase change process

Whenever a substance undergoes a phase change or an endothermic phase change then a cooling effect will be achieved and the extent will depend on the particular substance which is undergoing the change of phase. Usually processes like sublimation, melting, evaporation, etc. are the phase change processes that aid cooling effect. For example, sublimation of dry ice at a temperature of -78.5°C and at 1 atmospheric pressure would take away almost 573 kilojoules of heat per kilogram. Such figures are surprising and enticing for a thermal engineer. Usually, the problem associated with such processes is the handling of cooling substances. For example, handling of fluids is much easier than handling of solids. Therefore, in almost 95% of commercial refrigeration based on phase change employs a refrigerant which undergoes phase change during a thermodynamic refrigeration cycle. The amount of refrigeration produced during the phase change of the substance is given by:

$$Q = ml \tag{1.2}$$

where the mass of the substance is given by m which is undergoing the change of phase, l is the latent heat of the change of phase of the substance in use and Q is the amount of heat extracted during the change of phase of the substance. From equation 1.2 it is evident that if latent heat for the phase change is more than a less amount of the substance is required.

1.2.4. Expansion of liquids

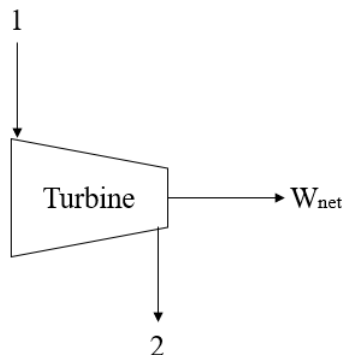


Fig. 1.1 Expansion through turbine

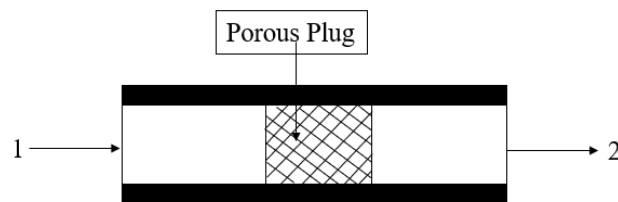


Fig. 1.2 Expansion through a porous plug

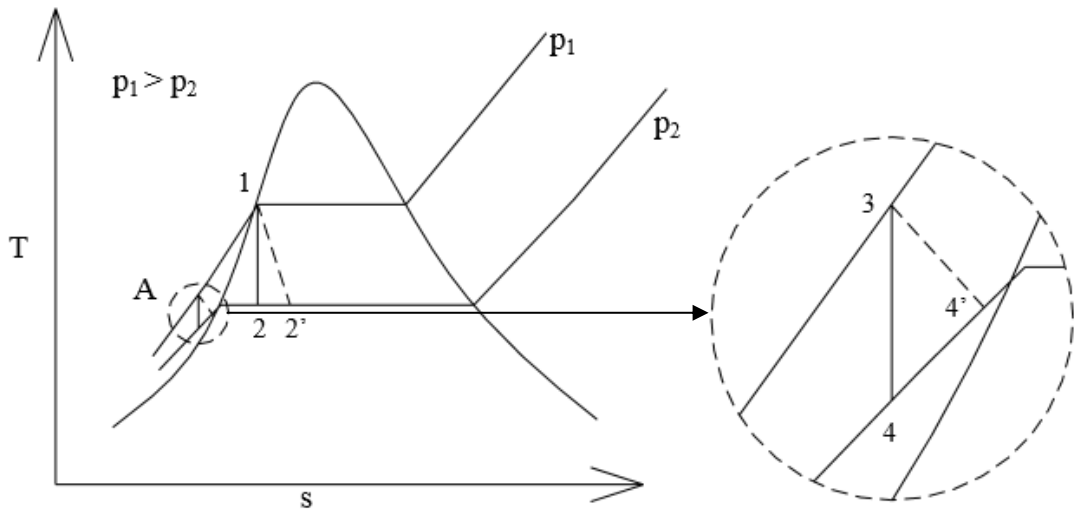


Fig. 1.3 Expansion of saturated liquid 1-2: Isentropic; 1-2': Isenthalpic, [RAC Lecture notes, IIT, Kharagpur]

Fig. 1.4 Expansion of subcooled liquid 3-4: Isentropic; 3-4': Isenthalpic [RAC Lecture notes, IIT, Kharagpur]

Expansion of liquids basically entails two ways, expansion through a turbine and expansion through a restricted channel, maybe a porous plug. If the expansion is through a turbine then there will be some net work output with the drop in temperature and pressure and the same is depicted in Fig.1.3 by a process 1-2. The process is isentropic, ideally, and the net drop in enthalpy (neglecting kinetic and potential changes) would then equate the specific work output. On the other hand, if the expansion is through a restricted channel then there will be a decrease in pressure and the process is highly irreversible due to frictional effect. Also, there will no net work output and if the porous plug or the process is considered to adiabatic then it can be seen that the process is isenthalpic, constant enthalpy, with the aid of first law or steady flow energy equation, provided the changes in kinetic and potential energy are negligible. This process is often famous by unique name, throttling process. The inlet condition plays an important role for the temperature drop. If the inlet is saturated liquid then the outlet will be a two-phase condition. Technically, during the expansion through a turbine the enthalpy of the outlet will fall because there is a network output and the entropy of the outlet for the throttling process would increase and the same is shown by 1-2'. The temperature however for both cases will be same. The temperature however can be seen that much lower than that of inlet because for the change of phase there is requirement of some energy which is provided by nothing else but fluid itself which causes its temperature to go down significantly. On the other hand, if the inlet is a subcooled liquid then the outlet will also be in liquid state and the temperature during isenthalpic process will fall less than that of isentropic process and also the temperature drop in either of the process is not significant as compare to the condition when inlet was a saturated liquid. Therefore, the expansion process of vapor compression refrigeration system is such that the outlet lies in two phase state.

1.2.5. Expansion of gases

Expansion of gases is generally a process in which pressure drops considerably along with the drop of temperature. To understand the processes involved in expansion, there are generally two ways that are discussed below

1.2.5.1. Expansion of gases through throttling

Similar to liquids, the expansion of gases, can also be done from a pressure which is higher to a lower one. Similar to liquids, expansion of gases follows two ways, through turbine and throttling. Through turbine, the process is isentropic same as liquid and throttling also a constant enthalpy. For ideal gases, enthalpy is a function of temperature only and if enthalpy remains constant then there will be no change in temperature. But practically as gases are not ideal therefore, either cooling or heating will occur through expansion of gases. Extent of such change will depend on the deviation of the gas with respect of ideal gas. The more the deviation, more will be the extent of cooling/heating and the same can be explained quantitatively by the joule-thomson coefficient.

$$\mu_{TJ} = \frac{[T \left(\frac{\partial v}{\partial T} \right) - v]}{C_p} \quad (1.3)$$

μ_{TJ} positive indicates cooling and negative indicates heating, the value corresponds to zero explains the gas to be an ideal one.

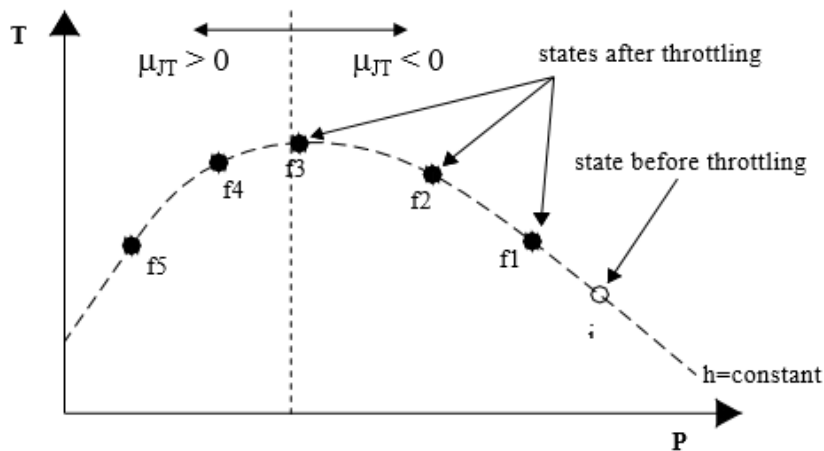


Fig. 1.5 T-P thermodynamic coordinates showing the expansion of gas [RAC Lecture notes, IIT, Kharagpur]

Figure 1.5 shows a constant enthalpy line with an initial condition of gas to be at state point i. Now, if we start throttling from this state point then heating will occur till point f3, this is because value of μ_{TJ} is negative and further throttling would result in decrease of temperature as the

coefficient value is positive on the left side. F3 is known as point of inversion, left of which causes cooling and right to the same causes heating. Therefore, it would bring a better result if the initial point is at the inversion point so that throttling to the left would always cause cooling. Fig. 1.6 shows few constant enthalpy curves. Most of the gases, with few exceptions, have their inversion temperature well above the room temperature and therefore their throttling would result in cooling.

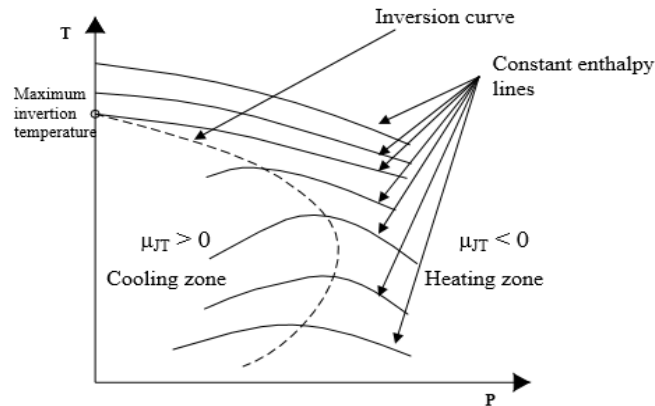


Fig. 1.6 Isenthalpic lines with inversion curve (locus of inversion points) [RAC Lecture notes, IIT, Kharagpur]

1.2.5.2. Expansion of gases through a turbine

Just like expansion of liquids, expansion of gases through turbine, adiabatically, also gives network output and due to this the outlet enthalpy will be lesser than the inlet. By the steady flow energy equation, it can be achieved that work output will be the difference of enthalpy of inlet and outlet, neglecting the kinetic and potential energy changes. This work always comes out to be positive, indicating that no matter what, the temperature of outlet will always decrease when a gas expands through a turbine. However, there is a limitation that the temperature difference decreases with decrease in inlet temperature. Therefore, adiabatic expansion of gases through turbines is used in couple with throttling so as to liquefy the gases. So, the first process will bring down the temperature lesser than inversion and then second will facilitate the cooling till liquefaction.

$$Q = h_1 - h_2 \quad (1.4)$$

where, h_1 be the inlet enthalpy of gas and h_2 be the outlet enthalpy.

1.2.6. Thermoelectric refrigeration

The genesis of this method of producing refrigeration was born in early 1800's and was officially penned down in late 1800's. Till then it was mostly seen as a laboratory fun and nobody really

showed much of an excitement to this until the mid-1900's, when there was the usage of semi-conductors to empower thermoelectric refrigeration. From then there has been a revolutionary work has been done and huge number of applications has been reported. This particular method gained huge popularity due to the fact that there was no moving fluid within this method. Also, the related components for the working of this refrigeration method are almost nothing in front of others. The only hurting fact regarding this method is the very less coefficient of performance (COP) with respect to other methods and this is primarily because of huge heat losses in the thermoelectric refrigeration, which has to be taken care of, otherwise the system fails.

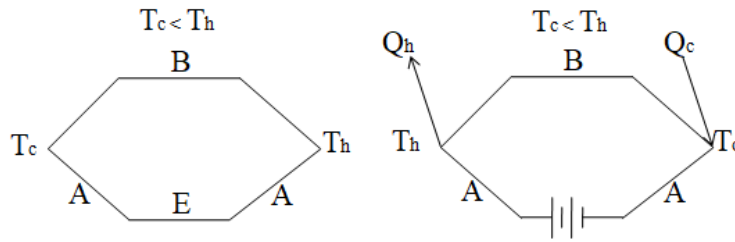


Fig. 1.7 Illustrations of peltier and seebeck effect

In relation to peltier effect, there are few more effects that are included in the computation of heat transfer by peltier effect, such as, seebeck effect, gives seebeck coefficient, joulean effect, due to the flow of current in a conductor with some finite resistance, conduction effect, which is due to the presence of temperature difference. Seebeck effect is such that an emf is generated when two junctions formed by two dissimilar metals are at different temperature. The emf generated can be mathematically represented as

$$EMF = al(T_1 - T_2) \quad (1.5)$$

where al is the seebeck coefficient and T_1 and T_2 are the temperatures at the junctions.

Contrary to this a temperature difference can be created by providing battery in between two different conductors with junctions initially at the same temperature. This effect was given by Jean C. A. Peltier in 1834. As the junctions will now be at a finite temperature difference due to applied electromotive force, therefore, the junction at the cold or lower temperature will aid the purpose of refrigeration effect whereas, the one having higher temperature will reject heat to the surrounding or to a heat sink if temperature goes considerably high. This stated theory is the basis for the refrigeration by thermoelectric effect or popularly known as peltier effect.

The heat transfer rate at each junction is given as

$$\dot{Q} = (\phi i)l \quad (1.6)$$

Where ϕ is the peltier coefficient and I is the current flowing in the conductors in ampere.

Another effect which is of importance is the thomson effect and according to this if there is a temperature gradient already existing in a conductor and then a current is passed through it then there will be a distortion in the temperature gradient. By the thomson effect we have following relation for heat transfer rate

$$Q = (\tau)I \frac{dT}{dx} \quad (1.7)$$

where, τ is the thomson coefficient.

Thermodynamically, τ , α and ϕ for two conductors A and B, such that τ_A , τ_B , α_A , α_B , ϕ_A , ϕ_B are the respective properties of A and B, are related as follows:

$$\phi_{AB} = \phi_A - \phi_B = \alpha_{AB}T = (\alpha_A - \alpha_B)T \quad (1.8)$$

$$\frac{\tau_A - \tau_B}{T} = \frac{d(\alpha_A - \alpha_B)}{T} \quad (1.9)$$

Thomson coefficient maps to zero value if the seebeck coefficient of both the materials is same.

Therefore, this can be seen that heat transfer rate due to peltier effect will become

$$\dot{Q} = \phi_{AB}I = \alpha_{AB}IT \quad (1.10)$$

Therefore, from the equation above to achieve higher rates of heat transfer at lower temperature, there are two ways, either to have a material with higher seebeck coefficient or supplying higher current. But supplying higher currents will lead to higher joulean effect. Therefore, choosing a better material with higher seebeck coefficient is a much better option.

Ideally, a thermoelectric material must exhibit higher electrical conductivity along with low thermal conductivity. This is to facilitate higher cooling and if the thermal conductivity is high then heat within the material will transfer more and the cooling effect will go down. Now, the pure metal fails the requirement because they have high thermal conductivity and insulators fails because they exhibit very low electrical conductivity. It was first by [A.F.Loffe \[1949\]](#); theory related to semiconductor thermoelement was first published and then on there are a lot of possibilities and achievements have been made to aid semiconductor material into the thermoelectric modules or peltier modules. Their reasonable low thermal conductivity and high electrical conductivity have

made their development in the field of thermoelectricity highly commercial. Semiconductor based thermoelectric refrigeration generally aid two types of semiconductors, p and n type, where p- type have a positive thermoelectric power, S_p , and on the contrary n-type holds negative thermoelectric power, S_n . Rate of refrigeration, coefficient of performance (COP) and temperature difference between hot and cold junctions are related by thermodynamics as follows

$$(T_2 - T_1) = \frac{(s_p - s_n)T_1 - \dot{Q} - \frac{1}{2}I^2R}{K} \quad (1.11)$$

$$\dot{Q} = (s_p - s_n)T_1 - (T_2 - T_1)K - \frac{1}{2}I^2R \quad (1.12)$$

$$COP = \frac{\text{Rate of Refrigeration effect}}{\frac{\text{Work done}}{\text{unit time}}} = \frac{(s_p - s_n)T_1 - (T_2 - T_1)K - \frac{1}{2}I^2R}{(s_p - s_n)(T_2 - T_1)I + I^2R} \quad (1.13)$$

Between two junctions, K is the thermal conductance. Equation 1.11 states that that if the two inherent irreversible effects, joulean and conductance, are removed then the present COP will map the COP of that of a Carnot refrigeration cycle.

In equation 1.11, we have demonstrated 3 performance parameters; COP, refrigeration effect, temperature difference, mathematically. Now, if we maximize this performance parameter then we will obtain a value of current which may be termed as an optimum current and this current will lead to maximization of the performance parameters. To get this optimum current mathematically, we need to differentiate the COP expression with respect to current and then equating it to zero. By doing so, following expression for optimum current and maximum COP will be attained

$$I_{optimum} = \frac{(s_p - s_n)(T_2 - T_1)}{R(\sqrt{1 + ZT_m} + 1)} \quad (1.14)$$

$$COP_{max} = \frac{\frac{T_1}{(T_2 - T_1)}(\sqrt{1 + ZT_m} - \frac{T_2}{T_1})}{(\sqrt{1 + ZT_m} + 1)} \quad (1.15)$$

where, Z is very important term and is a property parameter and is termed as figure of merit. T_m is the mean temperature of T_1 and T_2 . The expression for figure of merit, Z , is as follows

$$Z = \frac{(s_p - s_n)^2}{KR} \quad (1.16)$$

This can be easily seen that figure of merit depends on thermal conductivity, electrical conductivity and electrical contact resistance. For best performance, it is desired that a high figure of merit should be there. If the material of both the p and n type semiconductor is same then the

material will exhibit same thermal, K , and electrical, H , conductivity. Then figure of merit having maximum value will be given as

$$Z_{\max} = \frac{s^2 H}{K(1 + \frac{2r}{\sigma L})} \quad (1.17)$$

Where σ is the electrical resistivity and length of module is represented by L .

1.2.7. Adiabatic magnetization

E. Warburg in 1881 discovered the magnetocaloric effect based on which we have magnetic refrigeration. We know from the knowledge of thermodynamics and fluid mechanics that when a gas is compressed, the temperature of the gas rises and when it expands the gas cools down. Similarly, there are few materials which behave the same way analogously to the gases with compression being replaced by magnetization. Therefore, if these materials are magnetized then their temperature increases and when they are demagnetized their temperature will go down and this can be used to have a refrigeration effect. Certain paramagnetic salts when demagnetized can give a temperature closer to absolute zero.

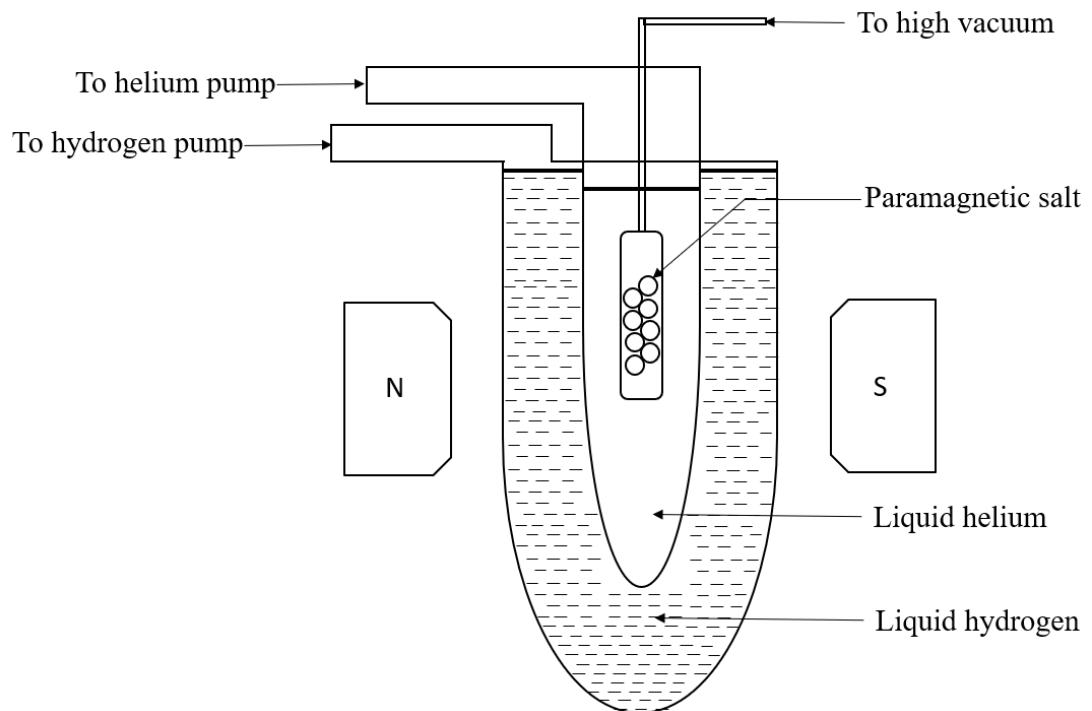


Fig. 1.8 Setup illustrating magnetic refrigeration

Consider there is a paramagnetic salt placed in a vacuum zone and consider each atom of the salt as a tiny magnet. If there is no magnetic field is there then all the magnets are aligned randomly and therefore the net magnetic force is zero. Now, if a magnetic field is applied then all the magnets will align themselves according to the applied magnetic field and this will need a work to be done and temperature raises meanwhile the process. As shown in the figure the salt is surrounded by helium and therefore, the temperature rise will be taken away by the helium. Now if suddenly the salt is demagnetized then they will try to again achieve their random places which would need some work to be done and if there is no source of heat available then their internal energy will decrease leading to decrease in temperature. This process can help in achieving temperature near absolute zero.

1.3 Advantages of thermoelectric cooling over the others

- The peltier units are very light weight and are solid state at the same time. Therefore, there is no liquid flowing and therefore no chance of any liquid leakage
- Also, there are no moving parts involved with these modules, making their operation very quiet.
- As only electricity is used to run them, therefore, there are no refrigerant involved, making them highly eco-friendly.
- Because there are no moving parts involved, therefore, there is no vibration involved in its working.
- It is very convenient to use these modules because it just involves basic electrical connections. Therefore, one just needs to apply voltage to it and it will self-limit its current. Also, it can be powered with a very simple system such as battery.
- These modules are bidirectional; therefore, one just needs to reverse the polarity and it will reverse the heat pumping direction.
- However, it is not an efficient device, because along with the pumped heat, it also adds on the joule effect. Therefore, an enormous amount of heat will be transmitted on the hot side if a higher current is drawn by the module. On the other hand, the adiabatic magnetization is the most efficient process but is not used here because the rate with which the temperature difference created is very low and due to this the process becomes slow. One way to achieve the cooling at higher rate is by using some special kind of alloys or by cascading several stages of these. However, an extensive research is going on in several institutes on this. Therefore, for current situation we had to drop this idea and switch ourselves to peltier cooling.
- Apart from all these, spot cooling, precise temperature control, high pumping capacity, light weight, etc., are few more advantages of peltier devices.

1.4. Introduction to Thermoelectric Cooling

A thermoelectric module, typically known as peltier module, is a thermoelectric cooler which is an electronic component based on semiconductor. This device can be considered as a small heat pump, this is because when a low DC voltage is applied to a thermoelectric module then a transit of heat will take place from one side to the other and due to this one face of a peltier module will be at low temperature then other or in other sense one face will be cooled and other will be heated simultaneously. The interesting thing here is that when the polarity of applied voltage is reversed then the effect will also reverse, that is, now the heat will flow in opposite direction. Therefore, a thermoelectric module can be used both ways, cooling as well as heating, consequently making it a decent device for temperature control. If we look closely then we can understand that the basic principle of a mechanical refrigerator based on vapor compression refrigeration cycle and a cooler based on peltier device will be same. In a mechanical refrigerator, there is an evaporator unit where the working fluid, a refrigerant, takes away the heat and undergoes a phase change due to the intake of thermal energy, and then this vapor refrigerant goes to compressor where this vapor is compressed and then it exchanges its heat with the environment in another heat exchanger, known as condenser. In a similar way, in a thermoelectric cooler, the evaporator is replaced by the sink attached to the cold side of device, condenser unit is mapped by the heat sink at the hot side of the device, refrigerant is superseded by doped semiconductor and the compressor is replaced by the DC power supply. The above stated argument is more pronounced in the fig. 1.9, below. For an initial encounter with a thermoelectric or peltier cooler, a simple behavior of the module is explained ahead to make an understanding of the capability of the module. In fig. 1.10, there is a peltier module shown with a DC power supply and a heat sink in a 3D view. The hot side of which is connected to a heat sink maintained at room temperature. A dc power supply is connected to the peltier device. When the DC power supply is ON then the cold side of peltier can go down to a temperature of -40°C and this can be termed as a dead point for ΔT , that is, no more temperature difference can be created anymore. Now, on the other hand if one starts supplying heat to the cold side of the peltier side then its temperature will rise, until its temperature will reach to that of the heat sink. This point can be seen as a dead state for the heat pumping capacity. Remember that previously it was stated that a peltier module can be considered as a small heat pump. Therefore, at the point where the temperature of the colder side maps to that of the heat sink, then at that point maximum rated heat pumping capacity of the peltier module is reached.

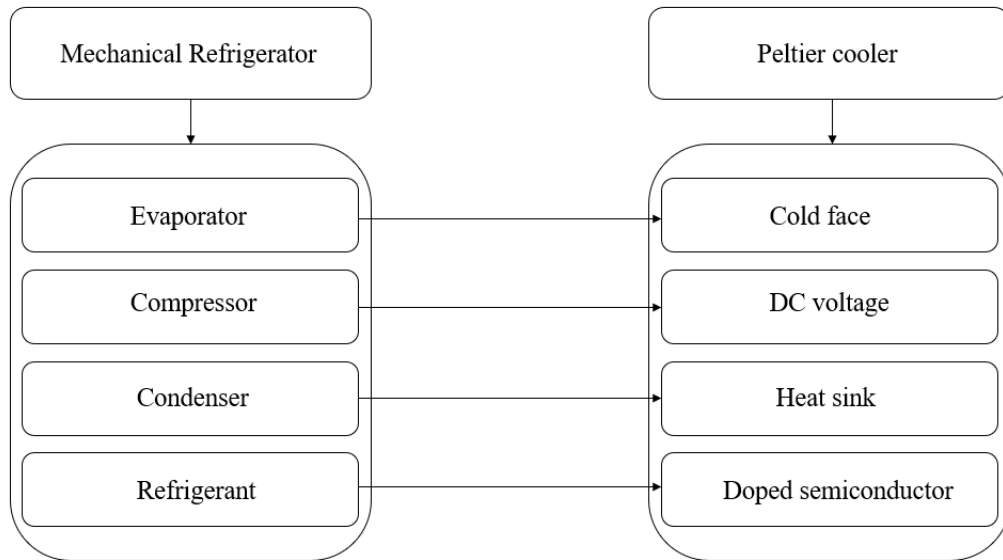


Fig. 1.9 Principle similarity between mechanical refrigerator and thermoelectric cooler

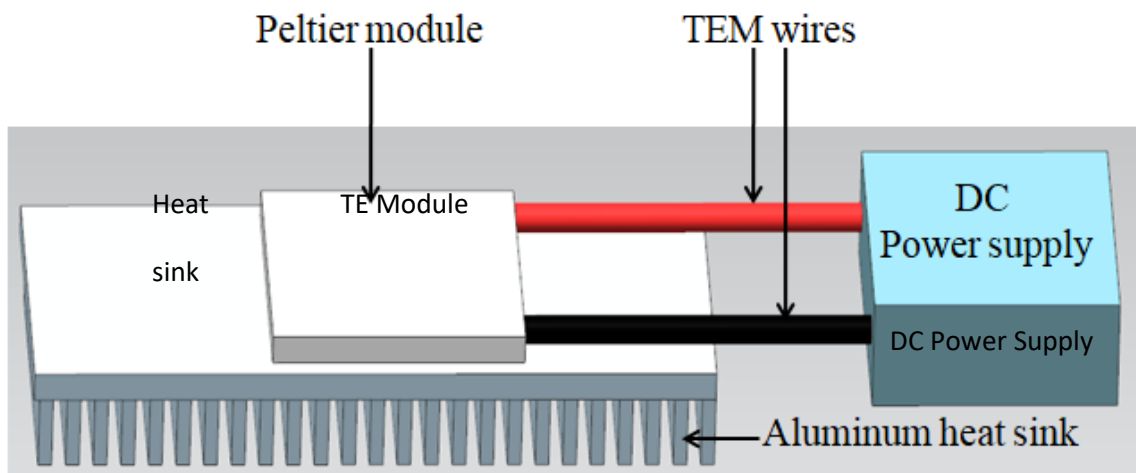
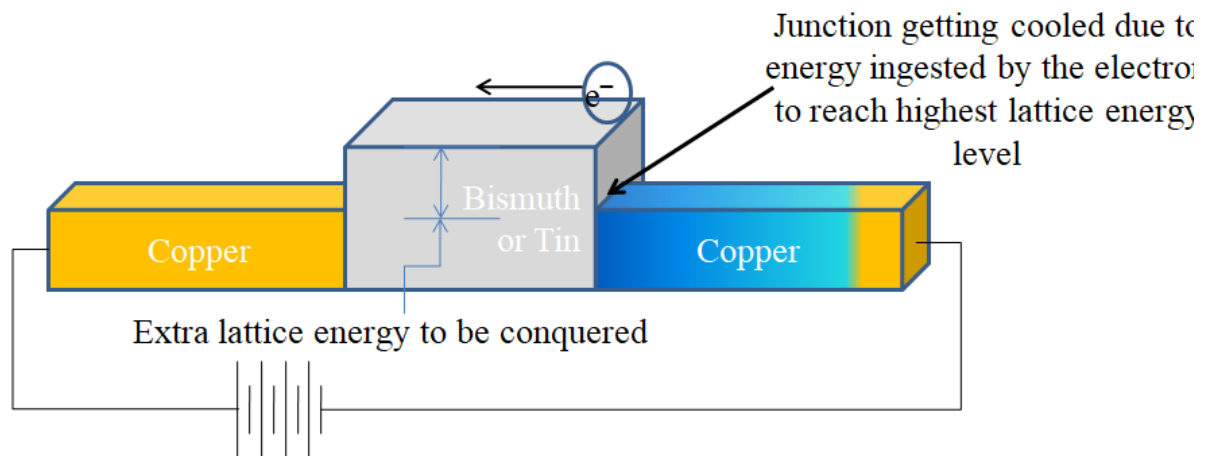
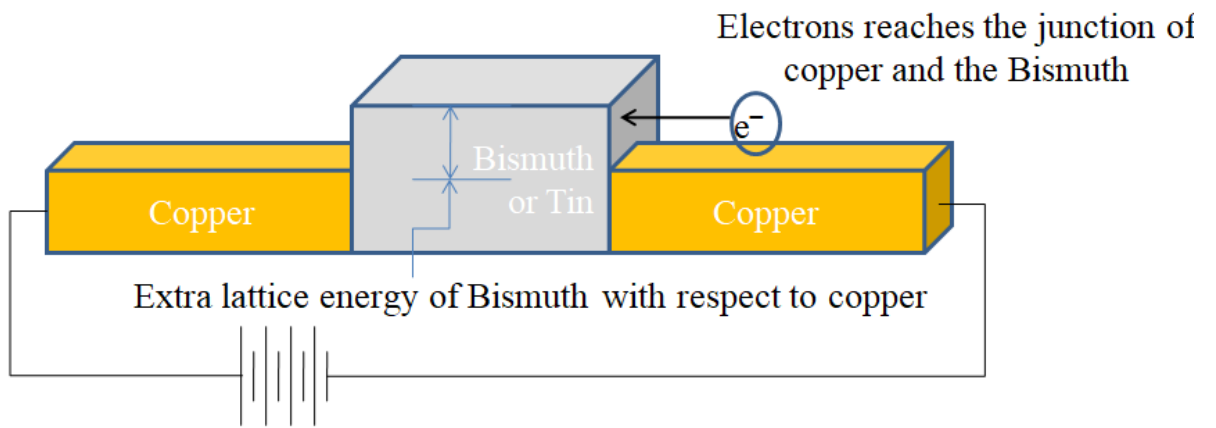
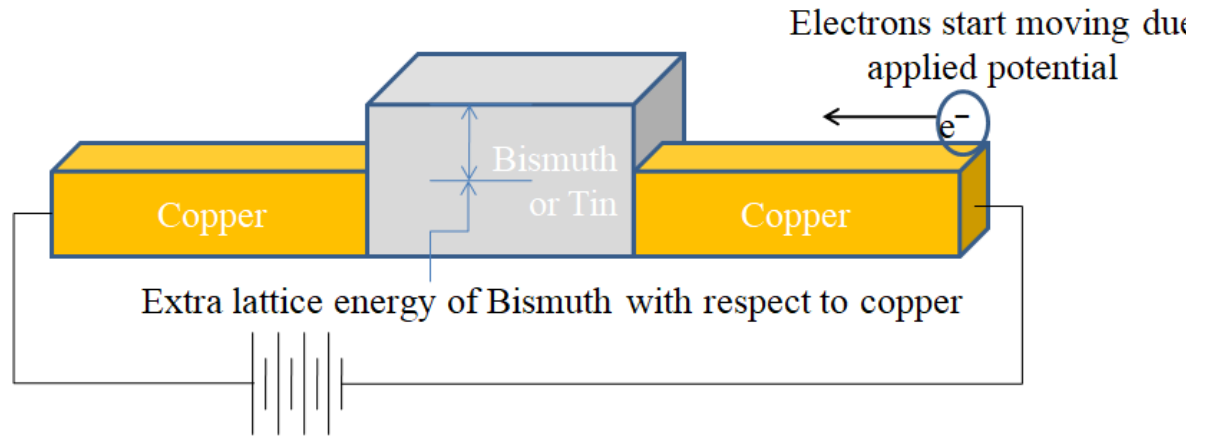


Fig. 1.10 A TE module with a heat sink

The traditional explanation of peltier effect and the basic physics behind cooling due to peltier module is defined below with the help of following fig. 1.11



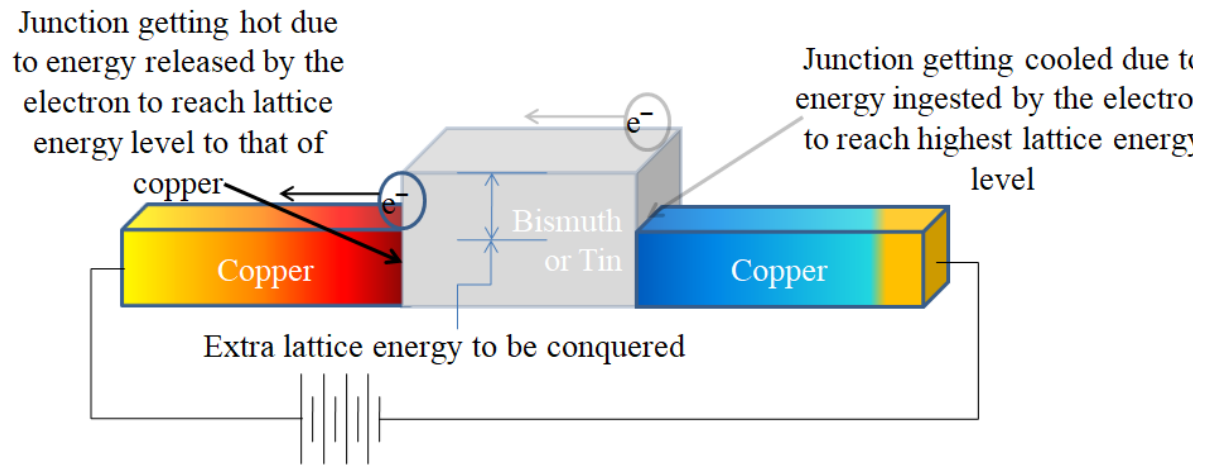
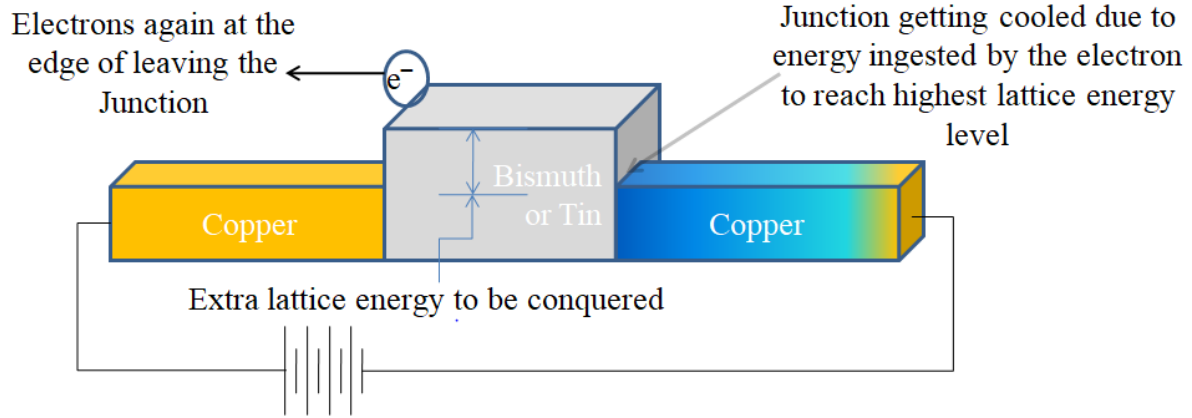


Fig. 1.11 Basic physics behind peltier effect

In this chapter, we will look into the beginning and then the successive progress in the field of thermoelectric effect. We will also look into some of the products that are have found their places in the field of peltier based refrigeration. At last we will try to conclude the survey both literatures based and market based, so as to come up with the idea that can help in our project.

2.1. Seebeck effect discovery

The seebeck effect discussed in Chapter 1 was not the first time when the world gets to know about thermoelectricity. There were instances way long before seebeck that gives clue to thermoelectricity. Fifty years before seebeck effect discovery, there was a Petersburg based academician, [Aepinus, 1951], who carried out his study on thermoelectric (TE) effect, in 1762, and the same was mentioned by [Lidorenko and Terekov, 2007]. In the race of TE discovery, Volta is also sometimes believed to be the first person and in regard to that there are numerous references by [Anatychuk *et al.*,2004]. This has been inferred from his bibliographical research that the first experimentation related to TE was done by A.Volta [Anatychuk, 1994] and [Anatychuk, 2004]. An article written by [Pastorino, 2009] has mentioned the Volta's role in invention of TE. The contribution is Volta is based on the happenings of Galvini's experiment [Korzhuiev *et al.*,2009]. In that experiment, Galvini observed that the dissected frog has twitched placed on dissimilar metal and Volta made an observation that such things happened because of the interaction of dissected frog's tissue with dissimilar metal. This seems somewhat similar to what seebeck has stated. There also an emf is generated due to the interaction of two metal's connecting junctions at different temperature. The contribution of A. Volta in the history of thermoelectricity is discussed in Direct energy conversion by [Decher, 1997] and few important points are listed below:

- The experiments conducted by A. Volta were based on the idea of discovering thermoelectromotive forces which are there due to difference in temperature. Whereas in the theory given by seebeck, the electrical nature or role in the effect of thermomagnetism has been rejected. Therefore, such an argument stated the two studies.
- According the discovery of A. Volta, the thermoelectromotive force origination was found whereas seebeck discovery was about the magnetic effect experienced due thermoelectric current which is there due to thermoelectromotive forces.
- A. Volta observations came almost 27 years earlier than that of Seebeck's.

Therefore, the timeline in the field of effects related to thermoelectricity has shown the trend, in which, there is Aepinus is at top and then there is the experimental studies by Galvini and A. Volta followed by Seebeck, Peltier and Thomson.

In a review book, written by Franz Peters, Schweigger and Ritter are observed to be the early witness of electrical currents because of temperature gradient, even before seebeck. But still Thomas Johanne Seebeck is said to be the first founder of thermoelectricity. On 16 August, 1821, during a session going at Berlin Academy of Sciences, seebeck talked about thermomagnetism as

stated by [Velmre, 2007]. After that he further talked about this on three separate events and published his results on thermomagnetism given by [Seebeck, 1823]. As explained above, Alessandro Volta was first to discover thermoelectric effect but it was Seebeck who analyzed different thermoelectric materials for the first time.

2.2. Peltier effect discovery

Jean Charles Athanase Peltier was a French watchmaker, who discovered the peltier effect. To see the heat absorption, he developed galvanometers and electrometers which were having very high precision and therefore, these has helped him to find out the absorption of heat at one of the junctions of two dissimilar metals, when an electric current is passed through it. In 1838, Emil Lenz found somewhat similar, that water can freeze if one junction is dipped in water of two dissimilar metal and an electric current is passed through it. He also observed that ice can be melted just by reversing the electric current [Lenz, 1838].

2.3. Thomson effect discovery

Thomson was the first to describe the thermoelectric effects theoretically, in 1851. He used the laws of thermodynamics to describe his observation. He also conglomerated the seebeck and peltier effects by giving one single expression with the help of thermodynamics. The theoretical description he gave were satisfactory and were in coherency with thermodynamics as stated by [Thomson, 1851]

2.4. First performance related calculations for thermoelectric devices

Lord John William Rayleigh was the first person to suggest power generation with the help of seebeck effect [Rayleigh, 1885]. The results of his work have some errors but still it is considered as the origin of the direct energy conversion concept. Solid-state devices that are made today for direct energy conversions are based on this principle of direct energy conversion as stated by Kaye & Welsh [1960]; Angrist [1965]; Sutton [1966]; Decher [1997]; Loffe [1957]; Eglis [1960]; Cadoff & Miller [1960]; Levine [1961]. Such devices have gained the interest of many technologists and scientists around the globe. At present, the real problem in the field of thermoelectricity is an advanced material that can give high performance out of the device and this is the main reason of these devices lacking their application in any broader application [Minnich *et al.*, 2009; Sootsman *et al.*, 2009].

2.5. First performance evaluation of thermoelectric devices

Inspired by the work of lord Rayleigh [Rayleigh, 1885], Edmund Altenkirch, a german scientist, published two theoretical papers. [Altenkirch, 1909], material properties that are relevant in electrical devices. Unger and Schwarz [2010]; Altennkirch [1911] gave the expression for efficiency of thermopile. Altenkirch stated his thermopile as an imperfect thermodynamic engine by comparing it with carnot engine. He also described the thermoelectric module effectiveness given in Altennkirch [1911]. He was the first one to make an argument that for a good

thermoelectric material, the seebeck coefficient must be high with high electrical conductivity and very low thermal conductivity.

2.6. Semiconductors as Thermoelectric Materials

Fedorovich Loffe, a Russian scientist, is the first one to do an extensive research for thermoelectric materials and in 1950's, he found out the possibility of semiconductors being a possible candidate for thermoelectric materials as given by [Joffe \[1958\]](#); [Kikoin and Sominskii \[1961\]](#); [Vedernikov and Iodarnishvili \[1998\]](#); [Joffe \[1950\]](#); [Jofe *et al.*, \[1956\]](#); [Anatychuk \[2002\]](#) Some of the key achievements of Loffe work in the field of thermoelectric effect is shown below:

- Loffe was the first one to give one of the most important terms in the calculative analysis of thermoelectric effect, figure of merit. Also, he was the first one to do the quality with respect to efficiency characterization in the field of thermoelectrics.
- For the very first time, the efficiency estimation of semi conductors for thermoelectric refrigeration and heating was done. Results were such that it attracts global attention for its practical usage.
- First thermogenerators based on PbS was made by Loffe and his colleagues [[Vedernikov and Iodarnishvili, 1998](#)].

The figure of merit given by Loffe is valid for only those peltier and seebeck devices for which are having constant parameters, that is, they are neither depending on temperature and nor on position [[Borrego, 1963](#)]. Also, the figure of merit is there in the efficiency formulae and these formulae only contain material properties. For cases, where temperature or position dependency arrives then effective figure of merit is calculated [[Mahan, 1991](#)]

2.7. Thermoelectric applications (1900-1980)

During and after world war there were many technologies that were taking birth and many were evolving at the same time. At that time, the thermoelectricity was studied extensively and was used for military and civilian applications. However, the economic growth of this technology was slow back then.

2.7.1. First thermoelectric based generator

M. T. Telkes was one of the initial trailblazers in the practical application of thermoelectricity. She did a thorough study on Pbs and ZnSb, which was already done 100 years back by seebeck [[Telkes, 1938](#)]. In [[Wood, 1988](#)], she reported that these materials are best suited for thermoelectric effect from the application point of view. First TE power generator was created by [Telkes, \[1947\]](#) and she also worked out first TE based refrigerator in 1953. It was then thought that TE technology will replace vapor compression refrigeration system-based refrigerators very soon. But after a decade only there was a huge decline in the research and the reason for that was low figure of merit. For a better performance of these modules, a figure of merit close to unity is desired.

The first TE element based on Bi_2Te_3 achieving a temperature of 0°C was achieved by [Goldsmid and Douglas, \[1954\]](#)

2.8 Thermoelectric application for space

Missions used in space exploration requires enormous energy for spacecraft to travel but at the same time, the light emitted by sun is not enough beyond Mars. Therefore, the heat produced by Sun is used for the spacecraft by NASA for several space exploration programs like; Apollo (1969-1972), Pioneer (1972), Viking (1976), Voyager (1977), Galileo (1989), Cassini (1997), and others.

2.9 New concepts in Thermoelectricity from 1980-Present

During 1990's the interest for creating material to have improved figure of merit has taken the pace and therefore, many researched to achieve this at nano scale at first as given in [Jebarzadi *et al.*, \[2012\]](#); [Dresselhaus *et al.*, \[2007\]](#); [Kanatzidis, \[2009\]](#). Some researchers have led to the discovery of some complex materials while others have failed [\[Snyder and Toberer, 2008\]](#)

2.10 Market survey: Home appliances

In this survey, we tried to understand what market has been offered by thermoelectricity so far. Therefore, we went through several products that have found some place in the market over the years.

Compact cooler

This particular product can be found in any random gas station of America or Europe. Fig. 2.1 shows the product and it includes a peltier module which has the capability of producing a temperature dip of 5°C . But the drawback lies with maintaining this temperature for longer duration. There is a fan provided on the outer heat sink to take care of the heat liberated by the module. Below is the fig. 2.1 showing a mini bar:



Fig. 2.1 A compact cooler, [\[Coleman, 2018\]](#)

Water dispenser

This product can often be seen at offices or waiting areas and is based on peltier refrigeration. The power rating of this product is similar to that of a car cooler. In this the cold side of the module is connected to the heat exchanger, rather than heat sink as that of the car compact cooler discussed above. Fig. 2.2 shows the peltier refrigeration-based water cooler:



Fig. 2.2 A peltier based water dispenser, [Quental, 2015]

Beer tender

This particular product uses similar kind of module than that of a car cooler. This particular appliance has capability of cooling 5 liters of beer. But it takes very long time to cool 5 liters of beer. However, it has one advantage over the car cooler, it can be connected to a regular power supply rather than only DC power supply. Below is the fig. 2.3 showing a beer tender:



Fig. 2.3 A peltier based beer tender, [Quental, 2015]

Mini bar

This type of refrigeration system is relatively a bigger version of a car cooler, which can be placed in a room. It uses the same power supply as that of car cooler and therefore it takes longer period of time to reach to its lower temperature and therefore, it is more difficult to maintain that lower

temperature. It is slow as compared to tradition refrigeration system. Below is the fig. 2.4 showing a mini bar:



Fig. 2.4 A minibar, [Quental, 2015]

Dehumidifiers

Small dehumidifiers can be seen any room or cabin to keep the humidity low. So as to achieve a lower humidity in the domain. The apparatus consists of a peltier unit, cold side of which is connected to a heat sink, such that when air flows through the heat sink it condenses the humidity present in air. It is comparatively a low power device. Below is the fig. 2.5 showing a dehumidifier:



Fig. 2.5 A dehumidifier, [Quental, 2015]

2.11. Conclusion from Literature

From the literature point of view, there has been a lot of work going on on the material improvement so that a much better performance can be achieved. Also, work is going on to improve the figure of merit as it appears directly in the efficiency formulae. From the market point of view, there are several products available but their working and efficiency is slow to replace the traditional refrigeration system. Also, no such product is there which is giving a temperature dip of significant lower negative figure.

2.12. Proposed aim

The aim is to make a prototype which must be having a capability of achieving a temperature difference of 50 with lowest temperature of -30°C so that a temperature of -50°C will be achieved similarly in commercial replica of this prototype. The basic idea will look something like the figure shown in the fig. 2.6 below:

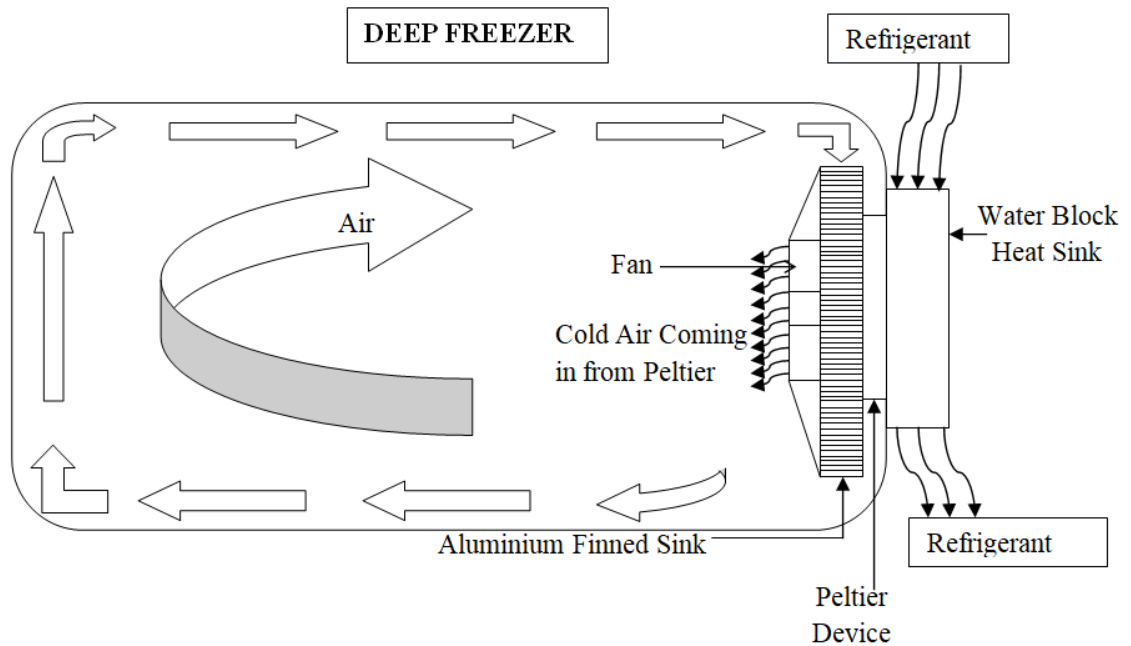


Fig. 2.6 Schematic of deep freezer concept

In this chapter, we will try to see the ways of installing thermoelectric modules. This is one of the crucial steps because TEM doesn't have holes in them and also the effects are experienced on the surface of the module, which is not super finish. Therefore, a rigid assemblage of module within in system is required.

There is specificity in their installation because there is some limitation associated with peltier modules. Generally, there are four ways by which a module can be installed:

1. Clamping
2. Bonding with epoxy
3. Soldering
4. Mounting pads and other material

3.1 Critical considerations for installation of thermoelectric module:

Desired performance of thermoelectric module may not be achieved if the installation of the same is not done properly within a cooling system. There are some key factors that should be in mind while the installation of a thermoelectric module.

1. So far by discussion, it might have been clear that peltier modules have compressive strength and it is true that they do. However, the concern is there in the shear strength which is relatively low. Therefore, while the installation of these modules in a cooling system one must take care of this fact that they are not placed such that a considerable shear load is applied on them.
2. Thermal resistance is one such factor which affects the performance of Peltier module drastically. One may disappoint in using them if thermal resistance is not taken care of properly. To reduce this, assure that the interfaces between the module and system must be free from any kind of dirt, a parallel and flat interface will result in better performance.
3. The hot and cold side of a peltier module must be clear to the user. There are generally three cases that one may come across. First case is when there is some printing done the face of module, like a company logo or the module number, for example, TEC1-12706, or anything else. In that case the printed side is the cold side of the module and the other being the hot. Second case is when there is no printing on the modules and one has an unsealed module with bare wires. In such case always remember that wires are always connected towards the hot side. Therefore, just by looking at the module, identification can be made, such that if the wires are pointing towards the user and are connected to the bottom then the top surface is the cold surface. Third case is when the module is sealed and wires are wrapped with red and black insulation. In that case, wires pointing towards the user and red at the right side will indicate that the cold surface is at the top.
4. When there is an application where the cooling is supposed to be done below the ambient temperature, the object that has to be cooled should be given enough insulation so that heat

inflow to the system is minimum. Installation of fan to the heat sink should not be in a way so that air is blown directly on to the surface of the object being cooled. Any direct contact of the system must be avoided so as to decrease the conduction losses.

5. A sealed peltier module must be used when cooling below dew point, this is because the frost and moisture will accumulate to the exposed surface and dew or frost entering the module may decrease the module performance substantially.

After going through all the important considerations for installation, let us discuss the methods of installation one by one. Usually the application dictates what method of installation is to be used.

3.2 Clamping

This method is generally used in most of the application and thus is very common out of all of them. To apply this method, following methodology must be followed:

- The surface between which peltier module is to be installed must be flat or must be made so by grinding to the extent that a flatness of 1mm/m must be achieved, in case a single stage module is used.
- If there is a requirement of multistage module then make sure that overall height or thickness variation must not go above 0.006mm.
- For mounting screws are to be used. Make sure that all the screws are arranged symmetrically so as to have an even pressure on the peltier module. To avoid, small screws must be used. M3 and M3.5 usually satisfies most of the application.
- Remove all the dirt and burrs from the mounting surface so as to avoid the unwanted thermal resistance.
- Thermally conductive grease must be used in between the module and contacting surface so as to reduce the thermal resistance. Apply a 0.002mm thickness of thermal grease on the module hot side and place the module on the decided heat sink with thermal grease coated hot side in contact with the heat sink. Now, there can be chances that the thermal grease is excessively applied. In that case push the module and along with that apply a turning motion, back and forth, until a little resistance is felt.
- Follow the same step for the cold surface and mate the cold surface with the object that is to be cooled.
- Now, apply the screws and bolt all the components, thermoelectric module, heat sink, and the object to be cooled, together using some washers and bolt them all together. Remember to have symmetry in applying the screws. Along with that focus must also be given in applying the pressure while bolting the screws. This is because if there is an uneven pressure is applied then it can affect the performance of the modules adversely and the worst-case scenario could be module damage. Uneven pressure or extreme pressure can even lead to buckling of the heat sink or the module resulting in an increase in the thermal resistance and decrease in performance. To avoid such things from happening, first hand tight all the screws until they can't be manually anymore. Then apply the pressure in a crosswise pattern

and there must be small increment in the torque in each turn so as to avoid any damage or extra localized pressure. Such a methodology can be implemented using a torque screwdriver. 30-100psi is the typical range of mounting pressure, or a clamping load of 0.5-1.2Mpa depending upon the application to application. The fig. 3.1, shows the sequence for two most common geometries.

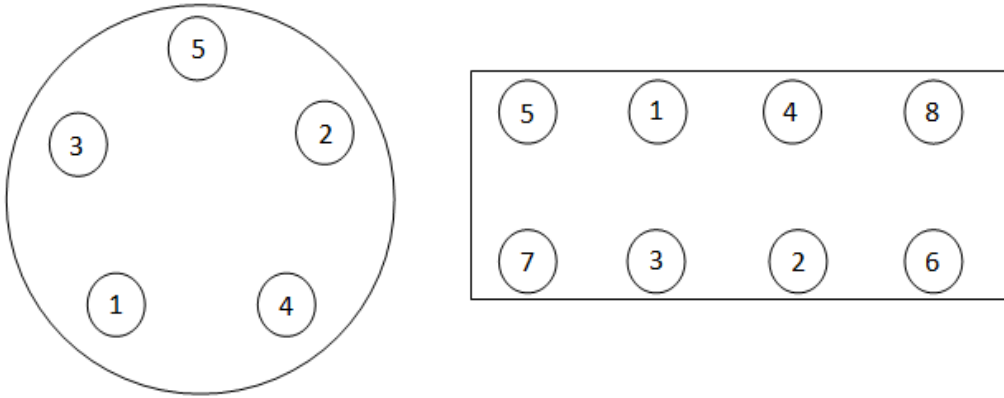


Fig. 3.1 Schematic showing the sequence of screw tightening in circular and rectangular geometry

There is a value of the torque or pressure that is given above. The necessary value for an application can be computed by using following expression:

$$T = \frac{s \times d \times CP \times A_M}{n} \quad (3.1)$$

s = Coefficient of torque

d = Bolt size in m

CP = Compression pressure in pa or psi

A_M = Overall module footprint area in m^2 or in^2

n = Number of screws

Torque per screw is in lb-in or N-m

For the tolerance due to thermal stresses in the system, washers much be used along with bolts. Usually, there is an extra amount of grease at the interface and after completing the assembly this grease usually comes out and thereby releasing the pressure on the module. This effect can be so pronounced that it can affect the performance of the module from 10-20%. To avoid such loss, wait for at least 60 minutes for the extra grease to squeeze out of the interface and then tighten again to make sure sufficient pressure is there on the modules. Re-tightening must be done in the cross-wise pattern only as explained above.

Other than thermal grease, graphite sheets can be used. Graphite sheets are a part of discussion because thermal grease usually has the tendency to dry out in case of elevated temperature and therefore, they will become inefficient in case of long-time application. There is a very little compromise in terms of thermal conductivity as compared to thermal grease, nearly less than 2%. If graphite sheet is going to be used along with epoxy then there will be a performance loss of nearly 10%. Therefore, application of peltier module is key factor to what material is to be used at the interface. There is another option of gap filler, thermal conductivity usually 1-5w/mK, made of silicone, which can be used. The bargain here is in terms of the shape complexity that they can handle. They also provide little protection towards vibration. The disadvantage lies in the term of thermal conductivity which is less compared to both thermal grease and graphite sheets.

3.3 Bonding with epoxy

Another method for mounting of thermoelectric module is epoxy bonding. In this case a highly thermally conductive epoxy is used to mount the module. But this method cannot be used in all the applications as the problem lies within the issue of thermal expansion. The material of module's base is ceramic and therefore, the thermal expansion of the system varies and therefore this method is not suggested for higher dimension module. There are certain things that needs to be remembered before using this method and the same are stated below:

- In epoxy bonding mounting method, the surface flatness is not a big issue as was in the case of clamping but still it is suggested to grind the mounting surface so as to avoid any unwanted resistance.
- Always make sure to remove all the burrs, dirt and degreasing of the mounting surface before applying epoxy or thermal grease.
- Now just like in the case of clamping, apply thermally conductive grease on the hot side of the module and place it with the module's hot side in contact with heat sink. Same as clamping, gently push the module to squeeze out excessive epoxy and also give a back and forth along with a turning motion until a resistance is felt.
- For the curing of epoxy, weight or clamp the module. Some epoxy requires oven curing and, in such cases, it is advisable to go through the datasheet of the module to see the maximum temperature withstand capability of the module.

3.4 Soldering

Soldering is preferable in those cases where the module has metallic surface. Soldering must be done only on one side of the module, preferably to the hot side. While soldering the maximum handling temperature of the module must be known so as not to exceed such limits while soldering.

Therefore, while soldering cooling must be done properly. If a small electronic circuit is to be cooled using thermoelectric module then that can also be soldered on the cold side of the module, but his should be keep in mind that there is no structural member attached to the circuit. A limitation associated with this method lies in the thermal expansion of the material same as in the epoxy bonding case. The thermal expansion of the soldering material, module surface and that of the heat sink may not be same and therefore, soldering method must not be use in case of larger modules. A series of steps which are kind of similar to previous methods but are must to be followed are given below:

Similar to epoxy method, flatness is not an important issue but still it must be taken care of to avoid any unwanted resistance or loss, therefore, grind must be done prior to soldering.

- Degreasing and removing any dirt or burr from the heat sink surface is also an essential to be done before soldering.
- Now for the soldering the surface of the heat sink that is to be mounted with the module must be tin. But this must be ensured that the selected solder's melting temperature must not be more than the maximum withstand temperature of the module.
- For the final step, soldering flux must be applied on the tinned heat sink and let the module to float on the pool of solder. If the module is dragging rather than floating then there is not enough flux and, in that case, remove the module and put some more flux material and apply the module again.

3.5. Mounting pads and other material

Silicon-based mounting pads are the some of the common material used for the mounting of the semi-conductors. But for the use in case of thermoelectric element they exhibit high thermal resistance which limits their application. However, there is one advantage of zero cleanup time. Other than thermal grease graphite can also be used as an interface material. Graphite works in cases where the usage is for longer period. However, they lack little bit of thermal performance when compared with thermal grease.

3.6. Reliability of thermoelectric module

The life of thermoelectric module generally depends upon the application in which it is placed. But in most of the cases the life of a thermoelectric module surpasses the life of related components. There have been instances where the module is in use for more than 20 years and still working fine. The industrial term for thermoelectric life is known as mean time between failure (MTBF). For an application such that where the module is used for cooling purposes using DC power will have a MTBF of 200,000 years. However, in case of thermal cycling this value is very poor at high temperature. Due to their solid-state construction their life is too high and therefore, for most o the applications they provide long and trouble-free solution. Usually, there are number of components and variables within a system and therefore, life of a thermoelectric module depends upon such

components and variables. Such complexities make it a difficult task to identify the exact life of a thermoelectric module. There are several talks about thermoelectric life in several literatures but the biggest problem with such conclusions and results from such studies are constrained to the experimental setups that are used in them. The atmospheric conditions, the heat sink selection, the module selection, the power supplied, the system geometry, etc. are some of the important factors that play an important role in the life of a module. For example, if a module is a part of structural member within the system then chances of failure are high. Similarly, if while clamping, the torque applied on screws is too high then there maybe bending in the modules and such bending will produce erroneous results and also prone to early damage. Using any module at threshold can also cause ill-time failure. The proper installation techniques that are discussed in chapter 2 are also crucial in determining the life of module. The installation factors that can affect module's reliability effectively are given below:

- The compressive mechanical strength of a thermoelectric module is very high but the shear strength is very low and this should be therefore, kept in mind while installation that a thermoelectric module should not serve the purpose of a support to a structural member. It is advisable to install module by clamping where there are chances of vibrations or shock.
- The peak value of the load due to compression in case of clamping, given by few manufacturers, is nearly 20 kilogram per square inch area of the module. Therefore, such value signifies that modules must not be placed in such a way that they can be drag out of the assembly by applying lateral force or any king of push or pull. This will indicate that modules are loosely bound within the assembly. Modules used in cascades are more vulnerable to such problems. Because of such reasons height tolerance values are given in the module mounting section. Stating again, a tolerance height of .002” is suggested when modules are used in array. In conclusion, loosely bounded modules can lead to their poor working and shorter life as well.
- While assembling the whole system, this should be ensured that no large unsupported mass should be in direct contact with the cold side of the module and if it is unavoidable due to some reasons then clamp the mass against the cold side with a rigid body so as to protect the module from shocks and vibration.
- When a thermoelectric module is used to cool below dew point then seals must be provided so as to save the module from corrosion and due to moisture or frost the thermal performance also deteriorates. A sealing should be provided either on the module itself or in between the cooled object and the heat sink. Silicon rubber or high insulating material may also be used to seal the gap between the cold object and the heat sink.
- Epoxy, soldering or other rigid mounting methods are not recommended in cases where high temperature differences are involved. This is because the thermal expansion of all the participating materials within the assembly is not equal. Modules often fail earlier than expected when are subjected to cycling. If thermal cycling is frequent with large temperature differences then it is advisable to use clamping method of mounting

thermoelectric module. For a general idea, module size greater than $225\text{mm}^2(15*15)$ must always be mounted by clamping method.

The reliability of thermoelectric module depends highly on temperature control. For the longer module life, on/off control must be replaced with proportional or linear control.

3.7. Reliability under high temperature exposure

Generally, there are two ways of thermoelectric failures, that is, failure due to degradation and catastrophic failure. Failure due to degradation is generally due to prolong working of the module under high temperature. Such condition affects the module performance adversely and therefore, it is not recommended to use thermoelectric module under high temperature for a longer duration. Such failures are also due to changes in material parameters or maybe a change in contact resistance.

3.8. Reliability under thermal cycling

Torch test is a term which is there when the module undergoes thermal cycling with elevated temperature at one or both sides of cycling. The damage that occurs under such category is of catastrophic type. But there are always some signs of degradation first before catastrophic failure. Usually, the failure under thermal cycling occurs because of varied coefficient of thermal expansion.

By stating the term thermal cycling, we actually meant the lowering and rising of temperature and this is because the application requires temperature control in such a peculiar fashion. This lowering and raising in some applications is of wide range due to which there is a chance of lowering in module performance. However, quantitatively there is no boundary line between a non-cycling and a cycling operation. But still for a basic understanding, one can say that a cycling is a process where the temperature is lowered and raised continuously over a longer period of time. Cycling processes are generally those operations where temperature control is automatic rather than manual. For more understanding, if a system is subject to thermal cycling for few times a day only then that case is not similar to the discussion here. However, there are several factors that have a good relation to the failure in case of thermal cycling and these factors are given below:

- Number of cycles
- Deviation of temperature over a cycle
- Higher limit of temperature in a cycle
- The rate with which temperature is changing

Considering such factors, a lower life pertains to higher number of cycles with higher temperature changing rates and higher peak temperature on the up-cycle side. On the other hand, a

better module life would be when number of cycles is small with a narrow temperature range and small rate with which temperature is changing along with lower limit of temperature in a cycle. From the argument so far, this must be realized that module life is not dependent on the time in which temperature cycles are happening, rather it is the number of cycles which is an important parameter here for the determination of the module life. Also, rather than using hours, it is the more appropriate to use MTBF. The term higher rated temperature will be discussed more in chapter 4. This higher rated temperature of a module has a substantial effect on the module's life. The higher the higher rated temperature, higher will be the module life. This argument is true even for the cases where the maximum cycle temperature is considerably higher than the higher rated temperature. Therefore, for a module with a lower maximum rated temperature, must be used for a low peak cycle temperature, if it is to be used for lower number of cycles. Other than that, a larger module with a greater number of couples or dices can fail early with respect to module with smaller area and lesser number of couples. This is because larger module will pertain to more thermal cycling during thermal cycling. Therefore, module selection based on application decides the life of module. As if an application requires more amount of heat to be extracted in a short time then a smaller module can't help and therefore, a larger module has to be used. There are ways by which usage of larger module can be avoided and such ways not only increases the life but can also result in an economic bargain in terms of using a high-power module.

3.9. Reliability to power cycle

The power cycle reliability is attributed to the power on and power off of the DC power supply. In general, thermoelectric applications, a module usually runs few times a day and therefore, not much of a power cycle problem is there. But in cases where precise temperature control is a need, the thermoelectric module may run through a torment of repeatedly ON/OFF, causing a considerable effect on the module's life. A general industrial standard, portrays a MTBF of 200,000 hours but this figure goes down as soon as there is a power cycle. Such a figure is enticing but this figure is not subjected to any kind of torture that is discussed above. Few power cycles experiments done by few industries showed that the above stated figure comes down to 125,000 hours of MTBF when cycled for 15 seconds of ON/OFF in combination.

This is to note that thermoelectric effects are reversible and this can be inferred from the fact that if we neglect that thermal and electric irreversibility, due to conduction and electrical resistances, respectively, from the expression of efficiency of thermoelectric module then we see that it maps the efficiency to that of a Carnot cycle and we know this well that all the processes that are in a Carnot cycle are reversible, therefore, by such analogy it can be inferred that a thermoelectric effect is reversible. Therefore, thermoelectric effect themselves never give rise to thermodynamic losses; it is the in-house electrical resistance and thermal conductance that give rise to such losses. Both of these resistances are dependent on ratio of length to cross-sectional area. Thermoelectric coefficients along with thermal and electrical conductivities are the transport properties. These properties are temperature dependent and this fact must be taken into account

while developing any model or theory. This is to note that this dependency is not substantial in case of low temperature difference, however, these effects are more pronounced in thermoelectric generation.

4.1. Modeling of a thermoelectric couple

Usually, a thermoelectric module is composed of several thermocouples, in hundreds. Therefore, once modeling of one couple is done then that can be extended to any number required. A typical thermoelectric couple is shown in fig. 4.1, below:

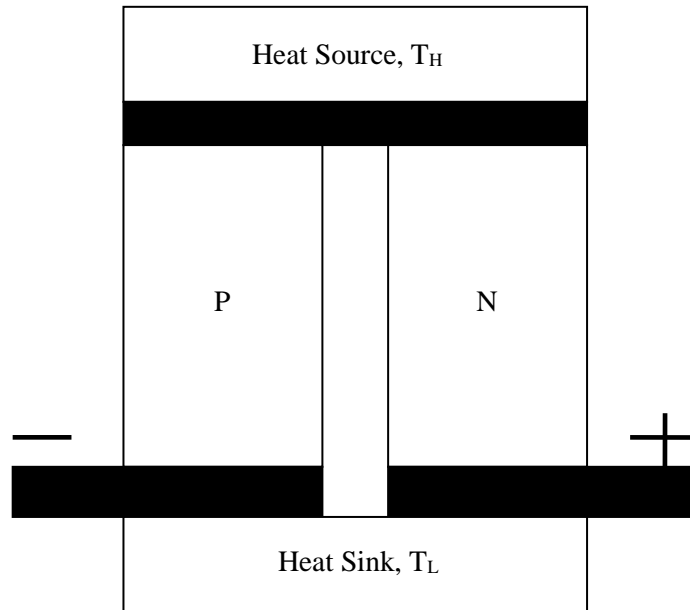


Fig. 4.1 A single couple thermoelectric refrigerator

In a thermoelectric device these couples are in series configuration electrically and thermally in parallel. For the theory that is followed here it is assumed that there is no thermal resistance between the heat sink or heat source and the thermocouples. Also, it is assumed that all the thermoelectric transport properties are not temperature dependent. One more important assumption to ease a bit of mathematics is that all the flow of heat is taking place within the couple and therefore, thermal losses due to modes of heat transfer are considered negligible. In the figure above the considered thermocouple is having equal dimension of P and N semiconductor. However, one can even take different lengths of semiconductors also but form factor, that is, length to area ratio is of great importance and the same has to be same for both semiconductors. There are several suggestions for considering tapered shaped thermocouples but it can be shown easily theoretically that it would have very little effect. Thermodynamically, the quantities that are of prime importance are COP and the refrigeration effect. If the irreversibility related to thermal and electrical resistance is neglected then the COP would map to the ideal COP, that is, that of Carnot COP, which is given by

$$COP = \frac{T_L}{T_H - T_L} \quad (4.1)$$

where, T_L is the absolute temperature of the heat sink and T_H is the absolute temperature of heat source. A peltier cooling at the source side will take place as soon as there will be a current, I , pass through the couple. This cooling is given by:

$$Q_C = (S_{PE} - S_{NE})IT_H \quad (4.2)$$

where, S_{PE} and S_{NE} are the seebeck coefficient of the semiconductors of the thermocouple, respectively. As discussed earlier, this cooling is hindered by thermal conductance and the electrical resistance or the joulean effect. Heat conduction rate is given by, $(T_2 - T_1)(K_P + K_N)$, where K_P and K_N are the thermal conductance and joulean effect is shared equally by the source and sink and the same is given by, $I^2(R_P + R_N)$, where, R_P and R_N are the thermal resistances of the semiconductors, respectively. By the stated argument, the total cooling effect is given by:

$$Q_C = (S_{PE} - S_{NE})IT_H - (T_L - T_H)(K_P + K_N) - \frac{1}{2}I^2(R_P + R_N) \quad (4.3)$$

For producing such cooling, there is an expenditure of electrical energy and the rate of which is given by:

$$Q_C = (S_{PE} - S_{NE})I(T_L - T_H) + I^2(R_P + R_N) \quad (4.4)$$

Here, the first term is the power required to overcome the thermoelectric voltage and second term is the resistive loss.

After, deducing the relation for the rate of refrigeration effect and the power required to produce that effect, it is now time to come to the relation of COP:

$$COP = \frac{(S_{PE} - S_{NE})IT_H - (T_L - T_H)(K_P + K_N) - \frac{1}{2}I^2(R_P + R_N)}{(S_{PE} - S_{NE})I(T_L - T_H) + I^2(R_P + R_N)} \quad (4.5)$$

From above equation this can be seen that Cop is also dependent on the current as does the cooling power. This is to notice very clearly that as current is increased the first term in the cooling power is also increased linearly but the joulean effect on the other hand increases as I^2 , therefore, it has a parabolic relation with the cooling effect. Therefore, as the current is increased, cooling power is increased, reaches a maximum value and then decreases. It can even go below zero, that is, negative value of cooling power and it happens when the joulean effect overpowers the cooling effect.

Due to this argument, there are two corresponding cases to the value of current. One corresponds to the maximum cooling power and other corresponds to the maximum COP. First, we discuss the current value for maximum cooling power. The current value corresponds to maximum cooling power can be obtained by differentiating the expression for maximum cooling power and then equating it to zero. By doing so, following value of current will be obtained

$$I_{qM} = \frac{(S_{PE} - S_{NE})T_H}{(R_P + R_N)} \quad (4.6)$$

Following this current, the COP will be given by

$$COP_q = \frac{\frac{ZT_H^2}{2} - (T_L - T_H)}{ZT_H T_L} \quad (4.7)$$

Where, Z is known as figure of merit and is given by

$$Z = \frac{(S_{PE} - S_{NE})^2}{(K_P + K_N)(R_P + R_N)} \quad (4.8)$$

Equation (4.8) shows that Z , temperature of heat sink and source are the depending factor on COP. However, ZT , a dimensionless figure of merit is more important term.

Now, the current for maximum COP can be obtained by differentiating the expression for COP and then equating it to zero. By doing so, following expression for current will be obtained

$$I_{COPM} = \frac{(S_{PE} - S_{NE})I(T_L - T_H)}{(R_P + R_N)\{(1 + ZT_m)^{\frac{1}{2}} - 1\}} \quad (4.9)$$

Here, T_M in the above equation is stated as mean temperature. Using this current value, the COP is given as

$$COP_{COPM} = \frac{T_H\{(1 + ZT_m)^{\frac{1}{2}} - (T_L/T_H)\}}{(T_L - T_H)\{(1 + ZT_m)^{\frac{1}{2}} + 1\}} \quad (4.10)$$

Usually, the current value lies between maximum cooling power and maximum COP. This is because taking current value by the method of optimum COP method will not give a practical value of cooling power. This is because using maximum COP will give a very less cooling effect, usually when the temperature difference is considerably low between sink and source. Therefore, in theory it might be case which leads to minimum electrical power consumption but in actual it is uneconomical in the thermoelectric sense.

There is one more optimization that can help to get the best out of thermoelectric module and that is, in terms of figure of merit. The aim should be to make the product $(K_P + K_N)(R_P + R_N)$ as small as possible. The stated argument can be fulfilled if the length to area ratio, form factor, satisfies the following equality:

$$\frac{L_N A_P}{L_P A_N} = \left(\frac{\rho_P \lambda_N}{\rho_N \lambda_P} \right)^{\frac{1}{2}} \quad (4.11)$$

If the above equation is satisfied then the following relation for figure of merit will be obtained,

$$Z = \frac{(S_{PE} - S_{NE})^2}{\{(\lambda_P \rho_P)^{\frac{1}{2}} + (\lambda_N \rho_N)^{\frac{1}{2}}\}^2} \quad (4.12)$$

This expression is usually preferred while explaining the figure of merit for the thermoelectric material. One of the most important terms of interest is the maximum temperature difference and it is very obvious that that value can be obtained when the cooling power or the COP maps to zero. By doing so, following relation for maximum temperature difference that can be reached using a peltier module is given by:

$$\Delta T_{MAX} = \frac{1}{2} Z T_H^2 \quad (4.13)$$

So far, we have been eliminating the fact that few properties were temperature dependent, however, for a realistic model these temperature dependent properties must be considered. We will first start with considering the temperature dependent properties and accounting them in the mathematical model and then we will see what can be eliminated or neglected within the mathematical model so that a closer model can be achieved.

4.2. Material properties with temperature dependency

Since we have introduced the argument by stating that the temperature dependent properties must be included in the modeling but still there are so many properties which have little to almost no

effect, therefore, a little simplified model is adopted here. For the beginning we will only consider three prime temperature dependent properties, that is, electrical resistance (R_E), thermal conductance (K_C), and the effective seebeck coefficient of the module (S_E). Rather than making it a general case from beginning, we start with the modeling for an industrial module, 71 couple and 6 amperes. Now, this can create a serious confusion about the modeling of other modules with a different temperature range and solution of this lie in a simple mathematical modification for any ' N_{New} ' numbers of couple module. However, the below presented mathematical modeling is valid for a temperature range of -100°C to $+150^\circ\text{C}$, which is a typical temperature range for most of the thermoelectric based application. There is a set of polynomial equations for all the temperature dependent properties for evaluating the module's performance. One important thing to note here is that all the temperature units will be in Kelvin. Also, the value of these properties provided by different manufactures are only the average values over a certain temperature range and by far such averages do not give much of a deviation but still for applications where a precise temperature control is required these averages may not be suitable.

4.2.1. Seebeck coefficient

Whenever, there is a temperature difference across or maintained across the thermoelectric device, then there will be an EMF generation and this EMF generation is proportional to the temperature difference due to which the EMF is generated. A third-degree polynomial is given below to define the seebeck coefficient as a function of temperature.

$$S_E = S_{E1} + S_{E2}T + S_{E3}T^2 + S_{E4}T^3 \quad (4.14)$$

where, S_E = Seebeck coefficient (volts/K)

T = Average module temperature

S_{E1} , S_{E2} , S_{E3} , S_{E4} are the coefficients for a module

This is here to note that the maximum heat pumping capacity of any module is an important term and that maximum is achieved when the temperature difference is zero. Therefore, to appreciate such notion, most of the relations and datasheet entries for a module are given when $\Delta T \rightarrow 0$. Therefore, equation 4.15 represents the coefficient of seebeck when $\Delta T \rightarrow 0$. However, if ΔT greater than zero then following relation will help, which includes hot side temperature and cold side temperature.

$$S_{ETC} \text{ or } S_{ETH} = S_{E1}T + \frac{S_{E2}}{2}T^2 + \frac{S_{E3}}{3}T^3 + \frac{S_{E4}}{4}T^4 \quad (4.15)$$

$$S_E = (S_{ETH} - S_{ETC})/\Delta T \quad (4.16)$$

where, S_{ETH} = Coefficient of seebeck at hot side temperature, T_H

S_{ETC} = Coefficient of seebeck at cold side temperature, T_C

$\Delta T = T_H - T_C$

4.2.2. Electrical resistance of module

Following is the expression of electrical resistance for a thermoelectric module as a function of temperature and similarly the way there were expressions for seebeck coefficient at $\Delta T \rightarrow 0$ and $\Delta T > 0$, the same way equation 4.17 and 4.18 defines the same respectively.

$$R_E = R_{E1} + R_{E2}T + R_{E3}T^2 + R_{E4}T^3 \quad (4.17)$$

$$R_{ETC} \text{ or } R_{ETH} = R_{E1}T + \frac{R_{E2}}{2}T^2 + \frac{R_{E3}}{3}T^3 + \frac{R_{E4}}{4}T^4 \quad (4.18)$$

$$R_E = (R_{ETH} - R_{ETC})/\Delta T \quad (4.19)$$

R_E = Electrical resistance of module in ohms.

T = Average module temperature in K

$R_{E1}, R_{E2}, R_{E3}, R_{E4}$ are the coefficients for a module

R_{ETH} = Resistance at hot side temperature, T_H

R_{ETC} = Resistance at cold side temperature, T_C

$\Delta T = T_H - T_C$

4.2.3. Thermal conductance of module

The expression for thermal conductance also follows the same trend as followed in seebeck coefficient and electrical resistance of module.

$$K_C = K_{C1} + K_{C2}T + K_{C3}T^2 + K_{C4}T^3 \quad (4.20)$$

$$K_{CTC} \text{ or } K_{CTH} = K_{C1}T + \frac{K_{C2}}{2}T^2 + \frac{K_{C3}}{3}T^3 + \frac{K_{C4}}{4}T^4 \quad (4.21)$$

$$K_C = (K_{CTH} - K_{CTC})/\Delta T \quad (4.22)$$

where, K_C = thermal conductance of module in W/k.

T = Average module temperature in K

$K_{C1}, K_{C2}, K_{C3}, K_{C4}$ are the coefficients for a module

K_{CTH} = Conductance at hot side temperature, T_H

K_{CTC} = Conductance at cold side temperature, T_C

$\Delta T = T_H - T_C$

4.2.4. Expressions of parameter in case of any general module

As specified earlier, the above expressions are for a 71 couple, 6 ampere modules. However, this may change according to requirement or application. There can be instances when a smaller module is required and there can be instances when a larger module is required with more numbers of couples in it. In such cases a modification is required in the expressions given above. Such modification is given below for the three properties stated above:

$$S_{E_{\text{new}}} = S_E \times \frac{N_{\text{new}}}{71} \quad (4.23)$$

$$R_{E_{\text{new}}} = R_E \times \frac{6}{I_{\text{new}}} \times \frac{N_{\text{new}}}{71} \quad (4.24)$$

$$K_{C_{\text{new}}} = K_E \times \frac{I_{\text{new}}}{6} \times \frac{N_{\text{new}}}{71} \quad (4.25)$$

where, $S_{E_{\text{new}}}$ = New module's coefficient of seebeck

$R_{E_{\text{new}}}$ = New module's electrical resistance

$K_{C_{\text{new}}}$ = New module's thermal conductance

I_{new} = Maximum current for new module

N_{new} = Number of couples in new module

4.3. Performance calculation for thermoelectric module

In chapter 1, we have already discussed about coefficient of performance for a thermoelectric module but those expressions are not the one used in industries. Because there are few variables within the expression that do not vary much from module to module and this is primarily because we have been using bismuth telluride as a thermoelectric material from a very long time and therefore material properties from module to module has not been changing much. Now, we discuss those parameters which are not material dependent and on the basis of which we will do the modeling. There are primarily five parameters that affect the performance of a thermoelectric/peltier module. These parameters are as follows:

- The input current to the module, I
- The heat pumped by the module, Q_C
- The input voltage to the module, V_i
- The temperature at the cold side, T_C
- The temperature at the hot side, T_H

4.3.1. Single stage module performance

We will discuss in chapter 6 that there are number of modules available in the market but not all the modules are modeled in a similar way. Modules in cascade have their own advantages and are modeled differently than a single stage. The modeling of a thermoelectric couple is done and now we will extend it further to an 'N' couple module. This has been already addressed that a thermoelectric module is a reversible device until we don't consider the conductance and joulean effect. Therefore, while modeling we first take a very general approach of first law of thermodynamics and the same is discussed below and also shown in fig. 4.2:

$$\begin{aligned} & \text{Heat given to the system or heat taken away by the module} \\ & - \text{Electrical work done on the system/module} = 0 \end{aligned}$$

In the above statement we have not considered any irreversible effect. On considering the two irreversible effects that are already discussed and further after rearranging we will get the following expression, in words:

$$\begin{aligned} & \text{Heat given to the system or heat taken away by the module} \\ & = \text{Electrical work done on the system/module} \end{aligned}$$

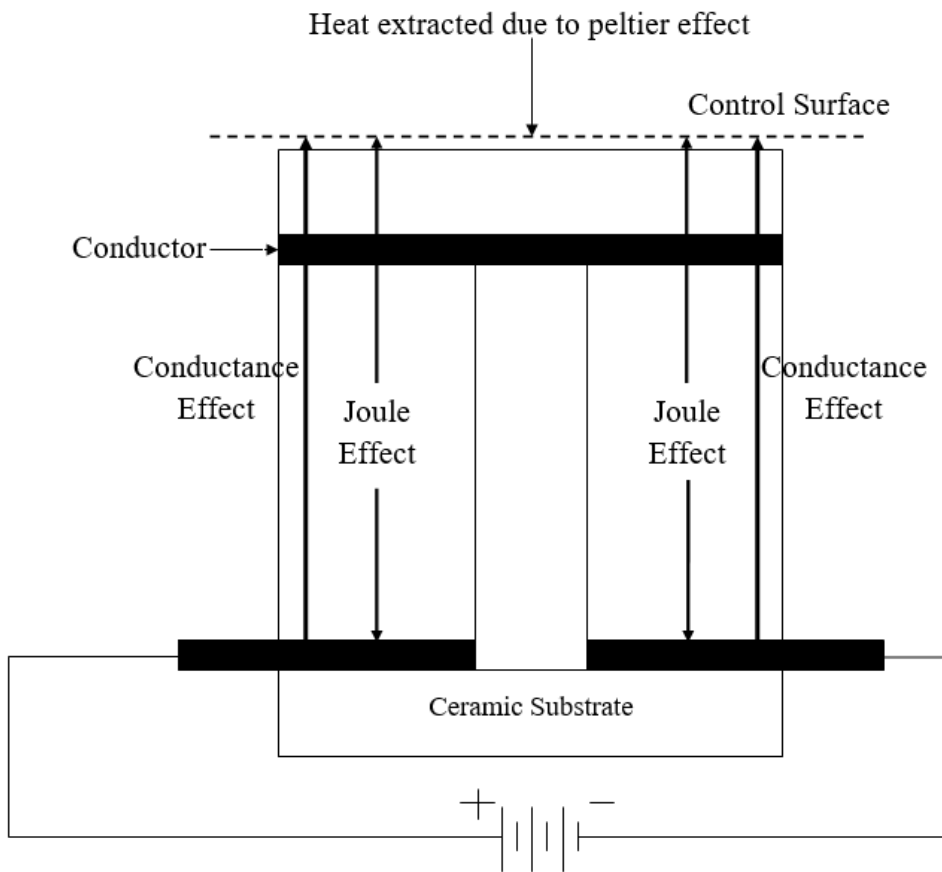


Fig. 4.2: Schematic of different phenomenon occur in a peltier module

The equations of all the effects have already been discussed above and the COP and other equations have already been explained (Refer equation 1.1—1.13).

4.4 Numerical analysis of thermoelectric module

In this section, we will first try to calculate the heat load that is needed to be drawn out of the system and then will look into suitable modules for such load.

4.5. Present scenario of freezing ice in freezer

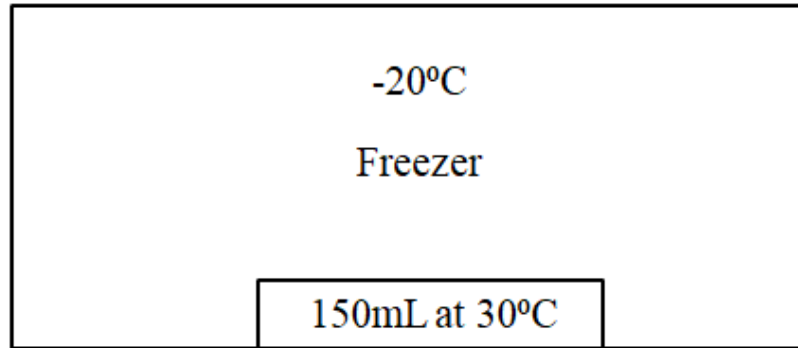


Fig. 4.3 Schematic showing a freezer at -20°C with a load of 150mL water at 30°C

Figure 4.3, shows a schematic of freezer at -20°C with a load of 150mL water at 30°C. Now, according to tests it takes almost 90 min for the water to convert into ice. Ice generally freezes to its center at almost -5°C. Therefore, the temperature of water will go down from 30°C to -5°C delivering sensible heat into the freezer compartment and there will be a delivery of latent heat at the time of phase change. 150 mL is the amount of water accompanied by an ice tray. For the sensible heat ice will be delivering a heat of:

$$Q_s = \dot{m}C_p\Delta T \quad (4.1)$$

where, Q_s = Sensible heat

\dot{m} = mass flow rate, Mass of water = 150mL

C_p = Specific heat of water, specific heat of water = 4.2KJ/Kg K

ΔT = Temperature difference

For the latent heat:

$$Q_l = mL \quad (4.2)$$

Where, Q_l =Latent heat

m = amount of water converting into ice, 150mL

L = Latent heat for water converting to ice, 334J/gm or 334000J/Kg

Therefore,
$$Q_{\text{Total}} = Q_s + Q_t \tag{4.3}$$

After doing all the calculations, for freezing of ice in 90 min,

$$Q_{\text{Total}} = 13.36\text{J/sec}$$

The total intermolecular energy which is needed to be taken care of would be 72150J.

Now, if we consider the only mode of heat transfer with in the freezer to be convection only then the Q_{Total} would be taken care of by convection only. For this the governing equation is given by:

$$Q = hA\Delta T \tag{4.4}$$

where, h = Convective heat transfer coefficient of air

A = Area across which heat transfer is taking place

ΔT = Temperature difference

4.6. Time reduction in ice making

Equating above equation with total heat will give the area, and by using that area and following the same process for deep freezer the total heat load would come out to be 40J/s for an ice making time of 30 min. Therefore, 40 joules of intermolecular energy are to be taken care of by the module and along with that there is a heat influx of 10 joules every second from the ambient. Therefore, in total 50 joules of intermolecular energy are to be taken care every second.

4.7. Calculation of heat influx

The calculation for heat influx is as follows:

Table 4.1 Values of different parameters for the calculation of thermal conductivity

Internal volume = 13225000mm ³	Convective heat transfer coefficient of air = 25W/m ² K
External volume = 18928000mm ³	Specific heat of air = 1.005KJ/Kg K
Thermal conductivity of surfaces = 0.25W/mK	Specific density of air = 1.367Kg/m ³
Thermal insulation within surfaces = Urethane foam	Deep freezer temperature = -50°C

Thickness of polyurethane foam = 20mm	Surrounding temperature = -20°C
Thermal conductivity of polyurethane foam = 0.019W/mK	Overall thermal conductivity = 0.8767 W/m ² K

4.8. Overall thermal conductivity:

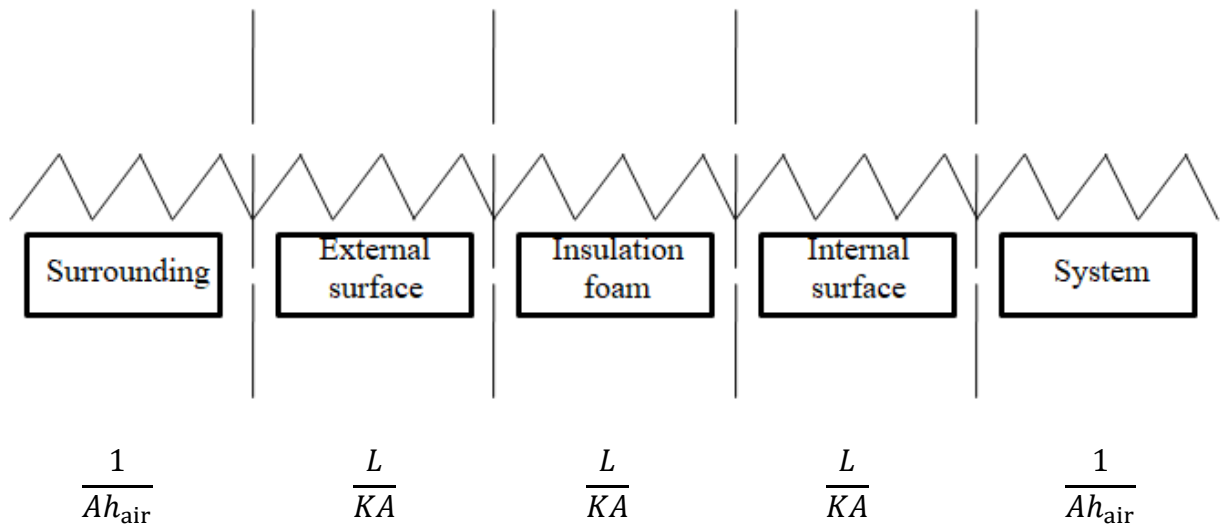


Fig. 4.4 Thermal resistances

4.9. Modules satisfying the requirement

As the heat load calculated to be nearly 50 watts, therefore, a module was required such that it has the capability of giving a temperature difference of 30-35 with a heat pumping capacity of 50 joules every second. To find such a module we ran our search with different vendors and modules available on different e-commerce website. The modules that fall into the category of our interest were:

Table 4.2 Selected modules for numerical analysis

S. No.	Module	$\Delta T_{max.}$	$Q_{max.}$ (Watts)	$V_{max.}$ (Volts)	$I_{max.}$ (Amperes)
1	TEC1-12706	68	66.7	17.2	6.1
2	TEC1-12707	68	70.1	17.2	7

3	TEC1-12708	68	81.8	17.3	8.2
4	TEC1-12710	68	110.5	17.2	10.1
5	TEC1-12715	70	150	16	15
6	TEC1-19908	68	145.8	26.9	8.5
7	TEC1-19911	68	188.4	26.9	11
8	TEC1-19912	68	191.7	26.6	11.3
9	TEC1-19914	68	216.1	26.9	12.6
10	TEC1-19916	68	243.5	26.9	14.2
11	TEC1-24105	68	118.1	33.1	5.8
12	TEC1-24106	68	124.6	32.7	6
13	MCTE1-12715L-S	68	130	15.4	15
14	FERROTEC_72001_127_110B	83	104	18.1	11
15	ETC-128-20-08-E	71	227	15.8	24
16	ET-127-20-15	74	128.7	15.7	13.1

These are the 17 modules of which we conducted the thorough study. The mathematical relations to find coefficient of performance, current, heat pumped, are given in chapter 5.

Using these relations, we tried to find out the possibility of using these modules under several conditions that will be discussed in the next chapter. As already explained, the heat pumping capacity increases with the current drawing capability of the module but at the same time the heat generated due to joule effect will also be there. Therefore, the trouble increases with increasing current. In the next chapter we will see that how the peltier effect sometimes reverses back even after reaching the lowest temperature. The reversal in the behavior is only due to abrupt rise in temperature of the hot side of the module. Therefore, one can straight away chose a module that have high current drawing capacity but then the rise in temperature due to joule effect will also increase. To be very specific, this is clear from the above equations that the cooling effect is proportional to the current but then on the other hand the heating is proportional to the square of current. Therefore, it is a much bigger problem than it looks like. Before we look into selected modules performance, let us first showcase the terms used in the performance table.

4.10. Important factors to be considered for module selection

Below is table 4.3 displaying all the essentials to be discussed in the module's performance:

Table 4.3 Performance parameters for module selection

I_{max}	Maximum current drawing capability	θ	Module's Thermal resistance
V_{max}	Maximum voltage drop capability	Q_c	Heat pumped out of system
ΔT_{max}	Maximum temperature difference capability	Q_{pel}	Power consumed by the module
$Q_{c,max}$	Maximum heat pumping capacity	Q_h	Heat pumped at the hot junction
ΔT	Temperature difference	COP	Coefficient of performance
R	Module's electrical resistance	I	Current drawn
α	Module's seebeck coefficient	T_h	Temperature at hot side

4.11. Calculative analysis of the module

Let us look into each module's performance one by one:

1. TEC1-12706:

Table 4.4 Performance evaluation of TEC1-12706

TEM Spec	
I_{max} (A)	6.1
V_{max} (V)	17.2
ΔT_{max} (K)	68
$Q_{c, max}$ (W)	66.7

Deep Freeze Temperature= -50° C

Units Req.	2	2	2	2
ΔT (K)	40	35	30	20
R (Ω)	2.09	2.08	2.06	2.03
α (V/K)	0.07	0.07	0.07	0.07
Θ (K/W)	1.75	1.76	1.77	1.80
Q_c (W)	25.00	25.00	25.00	25.00
Q_{pel} (W)	72.22	48.96	35.64	19.73
Q_h (W)	97.22	73.96	60.64	44.73
COP	0.35	0.51	0.70	1.27
I(A)	5.28	4.32	3.69	2.78
T_h (K)	263	258	253	243

As can be seen from table 4.4, specification of TEC1-12706, the maximum heat that can be pumped out of the cold surface is 66.7 watts. However, this figure can be achieved only if there is a zero-temperature difference across the surface of the module and the module is given maximum current. As discussed earlier, if the module will run at its maximum current then there will be huge amount of heat passed to the hot junction, which will then require a serious attention for the proper working of the module. As can be seen from the performance table, when the temperature difference is 40, the heat pumped to the hot side is almost 100 watts, which is really huge and at the same time the COP is quite low, 0.35. Also, two modules are required in any case of temperature difference. One important thing to understand here is the analyses done at different temperature difference, so as to meet all possible practical cases. For this very first module, the temperature difference of 50 is impossible as it gives a current value which is out of the scope of the module. Also, the electrical resistance of the module is very high. Therefore, a better module is required to meet the desired performance or cascading can be done to achieve the objective.

2. TEC1-12707:

Table 4.5 Performance evaluation of TEC1-12707

TEM Spec	
I_{\max} (A)	7
V_{\max} (V)	17.2
ΔT_{\max} (K)	68
$Q_{c, \max}$ (W)	70.1

Deep Freeze Temperature= -50°C

Units Req.	-	2	2	1
ΔT (K)	50	40	30	20
R (Ω)	-	1.80	1.80	1.77
α (V/K)	-	0.07	0.07	0.07
Θ (K/W)	-	1.52	1.54	1.57
Q_c (W)	-	25.00	25.00	50.00
Q_{pel} (W)	-	63.08	33.29	71.75
Q_h (W)	-	88.08	58.29	121.75
COP	-	0.40	0.75	0.70
I(A)		5.2	3.774	5.9801
Th (K)		263	253	243

This module was also giving erroneous value of current for a temperature difference of 50. Therefore, this module also failed to achieve the desired parameter. Also, in no case,

the COP is one. However, there is a possibility of achieving the desired performance if the temperature on the hot side is maintained at -30°C and in no other case the possibility is achieved. We are dealing with separate temperature differences because, the exact location of heat sink within the evaporator is not yet decided. Therefore, such a varied analysis is required. Therefore, either to choose a better module or cascading of the module can be tried.

3. TEC1-12708:

Table 4.6 Performance evaluation of TEC1-12708

TEM Spec	
I_{\max} (A)	8.2
V_{\max} (V)	17.3
ΔT_{\max} (K)	68
$Q_{c, \max}$ (W)	81.8

Deep Freeze Temperature= -50°C

Units Req.	-	2	1	1
ΔT (K)	50	40	30	20
R (Ω)	-	1.56	1.54	1.52
α (V/K)	-	0.07	0.07	0.07
Θ (K/W)	-	1.29	1.31	1.33
Q_c (W)	-	25.00	50.00	50.00
Q_{pel} (W)	-	58.37	117.60	55.47
Q_h (W)	-	83.37	167.60	105.47
COP	-	0.43	0.43	0.90
I(A)		5.32	8.09	5.59
T_h (K)		263	253	243

This module does have the capability of achieving the desired performance in two cases; at temperature difference of 20 and 30. But, then at the same time, the heat transported at the hot junction is enormous. However, the COP in first case is close to one. The electrical resistance of the module is still more than one. This is to keep in mind that the dependency of seebeck coefficient, thermal resistance and electrical resistance of a thermoelectric module has very less dependency on the temperature. Again, if the temperature difference goes beyond 30 then this module will fail to meet the desired performance. Therefore, in such cases, either a better module must be chosen or cascading must be done. The cascaded modules are readily available but the problem with such module is the size of their primary cooling surface, which is very less so as to be used in application like freezer. Therefore, a way has to be figured out to cascade

these modules without compromising the existing side. However, at present there are more modules to come, therefore let us analyze the next module.

4. TEC1-12710:

Table 4.7 Performance evaluation of TEC1-12710

TEM Spec	
I_{\max} (A)	10.1
V_{\max} (V)	17.2
ΔT_{\max} (K)	68
$Q_{c, \max}$ (W)	110.5

Deep Freeze Temperature= -50° C

Units Req.	-	1	1	1
ΔT (K)	40	35	30	20
R (Ω)	-	1.27	1.25	1.23
α (V/K)	-	0.06	0.07	0.07
Θ (K/W)	-	1.05	1.06	1.09
Q_c (W)	-	50.00	50.00	50.00
Q_{pel} (W)	-	122.00	83.04	45.11
Q_h (W)	-	172.00	133.04	95.11
COP	-	0.41	0.60	1.11
I(A)		8.976	7.387	5.514
Th (K)		258	253	243

First of all, the performance of the module at a temperature difference of 40 is not shown here, this is because it failed to give a permissible current value and even two modules were failed to give a temperature difference of 50. Two modules, if cascaded, can do the task. The heat liberated in case of temperature difference of 35 is huge, it is almost 175 watts, which is too heavy. Therefore, dragging out all the load out of this module at a temperature difference of 35 would create a huge problem at the hot junction. The good thing about this module is its COP which is more than one, in case of temperature difference of 20. However, the electrical resistance of this module is still more than one. A temperature difference of 50 is still not achieved in this module also, therefore, a better module must be used or option of cascading may also work.

5. TEC1-12715:

As can be seen from the analyses below, this is the first module which showed some possibility of achieving the desire of deep freezer. However, two such modules are required to achieve such desire. Also, the heat pumping capacity of the module is improved then previous versions of TEM. The heat liberated is high in terms of temperature difference of both 40 and 50. Table 4.8 shows that for temperature difference of 50, two modules are needed. This is because then, two modules will be used and the analyses here is for one module. The current drawn in case of both 40 and 50 is quite high, which implies that a good amount of heat will be liberated and a power source of power is required. The COP in case is temperature difference of 20 is close to 1.5, which is a good figure to work on with. But still, if there is a module which can alone handle the situation of temperature difference of 50 then that would be the final deal for deep freezing. Therefore, let us keep our search going and let’s look into the next possible case.

Table 4.8 Performance evaluation of TEC1-12715

TEM Spec	
I _{max} (A)	15
V _{max} (V)	16
ΔT _{max} (K)	70
Q _{c, max} (W)	150

Deep Freeze Temperature= -50° C

Units Req.	2	1	1	1
ΔT (K)	50	40	30	20
R (Ω)	0.79	0.78	0.77	0.76
α (V/K)	0.06	0.06	0.06	0.07
Θ (K/W)	0.78	0.79	0.81	0.81
Q _c (W)	25.00	50.00	50.00	50.00
Q _{pel} (W)	100.62	115.54	62.90	35.22
Q _h (W)	125.62	165.54	112.90	85.22
COP	0.25	0.43	0.79	1.42
I(A)	9.56654	10.6937	7.88	5.99
Th (K)	273	263	253	243

6. TEC1-19908:

This module is almost similar to TEC1-12715, except the current drawing capacity, which is a merit point for this module. But still the heat liberated by this module is higher than that of 12715 in all cases. At the same time, this too can’t alone handle the load of creating a temperature difference of 50. COP also is lagging than previous case

Therefore, except the part of current drawn, there is not one performance parameter in which it outperforms 12715. Therefore, this module is not recommended over 12715. One more thing where this fails to overpower 12715 is the price. 12715 is way cost effective than 19908. Also, the availability of 19908 is not very easy in India. Therefore, using this instead of 12715 would lead to a lower COP with more sophisticated heat handling setup than 12715.

Table 4.9 Performance evaluation of TEC1-12715

TEM Spec	
I_{\max} (A)	8.5
V_{\max} (V)	26.9
ΔT_{\max} (K)	68
$Q_{c, \max}$ (W)	145.8

Deep Freeze Temperature= -50° C

Units Req.	2	1	1	1
ΔT (K)	50	40	30	20
R (Ω)	2.38	2.36	2.35	2.33
α (V/K)	0.10	0.10	0.10	0.10
Θ (K/W)	0.79	0.80	0.80	0.81
Q_c (W)	25.00	50.00	50.00	50.00
Q_{pel} (W)	111.14	131.30	68.09	37.64
Q_h (W)	136.14	181.30	118.09	87.64
COP	0.22	0.38	0.73	1.33
I(A)	5.88	6.65	4.778	3.606
Th (K)	273	263	253	243

7. TEC1-19911:

This module has got the maximum heat pumping capacity, so far discussed. But still this is not better than 12715, one because it transports more amount of thermal energy than 12715 in case of temperature difference of 50 and second because it expensive than 12715. However, it outperforms 12715 in case of current drawn. But then the potential difference across the terminal is high. Therefore, a better module is still not discovered for the application.

Table 4.10 Performance evaluation of TEC1-19911

TEM Spec	
I_{\max} (A)	11
V_{\max} (V)	26.9
ΔT_{\max} (K)	68
$Q_{c, \max}$ (W)	188.4

Deep Freeze Temperature= -50° C

Units Req.	2	1	1	1
ΔT (K)	50	40	30	20
R (Ω)	1.84	1.82	1.81	1.80
α (V/K)	0.10	0.10	0.10	0.10
Θ (K/W)	0.61	0.62	0.62	0.62
Q_c (W)	25.00	50.00	50.00	50.00
Q_{pel} (W)	117.56	115.43	62.87	34.06
Q_h (W)	142.56	165.43	112.87	84.06
COP	0.21	0.43	0.80	1.47
I(A)	6.77135	6.93	5.1042	3.8136
Th (K)	273	263	253	243

This module has got the maximum heat pumping capacity, so far discussed. But still this is not better than 12715, one because it transports more amount of thermal energy than 12715 in case of temperature difference of 50 and second because it expensive than 12715. However, it outperforms 12715 in case of current drawn. But then the potential difference across the terminal is high. Therefore, a better module is still not discovered for the application.

8. TEC1-19912:

This is the first module that stands still in all temperature difference. However, the quantum of thermal energy transported to the hot junction during the temperature difference of 30 is nearly 350 watts, which is way too high and the COP corresponding to this temperature difference is 0.17, which is very less. Therefore, to extract 50 watts it liberates 350 watts which is an unacceptable deal. The COP in case of temperature difference of 20 is nearly 1.5 which was also there in the case of 19911 and 12715. Therefore, this module is capable of performing in all situations but still the bargain for this deal is unacceptable, as the heat liberation in few cases is too high.

Table 4.11 Performance evaluation of TEC1-19912

TEM Spec	
I_{\max} (A)	11.3
V_{\max} (V)	26.6
ΔT_{\max} (K)	68
$Q_{c, \max}$ (W)	191.7

Deep Freeze Temperature= -50° C

Units Req.	1	1	1	1
ΔT (K)	50	40	30	20
R (Ω)	1.77	1.75	1.72	1.73
α (V/K)	0.10	0.10	0.11	0.10
Θ (K/W)	0.60	0.61	0.62	0.61
Q_c (W)	50.00	50.00	50.00	50.00
Q_{pel} (W)	289.56	115.03	62.71	33.91
Q_h (W)	339.56	165.03	112.71	83.91
COP	0.17	0.43	0.80	1.47
I(A)	11.49	7.04	5.188	3.8732
Th (K)	273	263	253	243

9. **TEC1-19914:** Table 4.12 Performance evaluation of TEC1-19914

TEM Spec	
I_{\max} (A)	12.6
V_{\max} (V)	26.9
ΔT_{\max} (K)	68
$Q_{c, \max}$ (W)	216.1

Deep Freeze Temperature= -50° C

Units Req.	1	1	1	1
ΔT (K)	50	40	30	20
R (Ω)	1.60	1.59	1.58	1.57
α (V/K)	0.10	0.10	0.1	0.1
Θ (K/W)	0.53	0.54	0.54	0.54
Q_c (W)	50.00	50.00	50	50
Q_{pel} (W)	238.15	113.23	61.96	33.03
Q_h (W)	288.15	163.23	111.96	83.03
COP	0.21	0.44	0.81	1.51
I(A)	10.748	7.2633	5.36	3.97
Th (K)	273	263	253	243

This module is a successor of TEC1-19911 but with some merits in it. First being the amount of heat rejection at the hot junction, which is almost 50 watts less than the previous case of 19911. Also, the current drawn is less than the previous case and due to which the COP is little higher than the previous module. The COP in the case of temperature difference of 20 has actually crossed 1.5 for the first time in all the cases discussed above. However, the electrical resistance is almost twice than that of 12715.

10. TEC1-19916:

19916 is again little better than 19914, but the cost difference is also rising along with the successor. The cost of this module is almost 10 times the cost of 12715, which makes it highly cost ineffective. If we compare this price hike with respect to the performance hike, then it is easy to see that the rate with which the price is rising is way too much with respect to performance rise. Therefore, we have got a module here which can handle the desired temperature difference but is highly cost ineffective. So, the search for a cost effective yet performing module is still not completed.

Table 4.13 Performance evaluation of TEC1-19916

TEM Spec	
I_{\max} (A)	14.2
V_{\max} (V)	26.9
ΔT_{\max} (K)	68
$Q_{c, \max}$ (W)	243.5

Deep Freeze Temperature= -50° C

Units Req.	1	1	1	1
ΔT (K)	50	40	30	20
R (Ω)	1.42	1.41	1.40	1.40
α (V/K)	0.10	0.10	0.10	0.10
Θ (K/W)	0.47	0.48	0.48	0.48
Q_c (W)	50.00	50.00	50.00	50.00
Q_{pel} (W)	225.23	113.31	61.96	32.51
Q_h (W)	275.23	163.31	111.96	82.51
COP	0.22	0.44	0.81	1.54
I(A)	10.97	7.6426	5.6348	4.13
Th (K)	273	263	253	243

11. TEC1-24105:

This module, as can be seen from its nomenclature, is a bigger size module. The size of this module is 60mm x 60mm. therefore, before going into any performance parameter, we already have one advantage with module, which the effective heat pumping is, or in other terms a bigger evaporator. A bigger evaporator can accompany a bigger heat sink which means a bigger evaporator at the end. Therefore, this one is having advantage bigger cooling surface area. However, the capacity of this module is lower than 12715. Due to small capacity the module cannot withstand a heat load of 50 watts to create a temperature difference of 50. Therefore, either to choose a different module or cascading of the modules must be done. The cost of this module is also very high due the number of couples placed in it. Let us have a look at its successor.

Table 4.14 Performance evaluation of TEC1-24105

TEM Spec	
I_{\max} (A)	5.8
V_{\max} (V)	33.1
ΔT_{\max} (K)	68
$Q_{c, \max}$ (W)	118.1

Deep Freeze Temperature= -50° C

Units Req.	1	1	1	1
ΔT (K)	50	40	30	20
R (Ω)	4.29	4.23	4.17	4.11
α (V/K)	0.12	0.13	0.13	0.14
Θ (K/W)	0.94	0.96	0.97	0.98
Q_c (W)	25.00	50.00	50.00	50.00
Q_{pel} (W)	112.47	175.67	75.79	41.79
Q_h (W)	137.47	225.67	125.79	91.79
COP	0.22	0.28	0.66	1.20
I(A)	4.46	5.87	3.8173	2.8743
T_h (K)	273	263	253	243

12. TEC1-24106:

Table 4.15 Performance evaluation of TEC1-24105

TEM Spec	
I_{\max} (A)	6
V_{\max} (V)	32.7
ΔT_{\max} (K)	68
$Q_{c, \max}$ (W)	124.6

Deep Freeze Temperature= -50° C

Units Req.	2	1	1	1
ΔT (K)	50	40	30	20
R (Ω)	4.09	4.04	4.04	3.92
α (V/K)	0.12	0.12	0.12	0.13
Θ (K/W)	0.92	0.93	0.93	0.96
Q_c (W)	25.00	50.00	50.00	50.00
Q_{pel} (W)	111.94	164.05	74.55	41.17
Q_h (W)	136.94	214.05	124.55	91.17
COP	0.22	0.30	0.67	1.21
I(A)	4.54	5.785	3.866	2.91
Th (K)	273	263	253	243

Being successor of 24105, there is not much significant change in any factor. Therefore, these two modules that are just discussed have bigger effective cooling area along with a COP greater than one in case of temperature difference of 20 and along with that their price is also too high. Therefore, these modules are of no use to us for the specific application we are looking for.

As we were in contact with few vendors, therefore, the upcoming four module's data were provided from the vendors and are special purpose module.

13. MCTE1-12715L-S: Table 4.16 Performance evaluation of MCTE1-12715L-S

TEM Spec	
I_{max} (A)	15
V_{max} (V)	15.4
ΔT_{max} (K)	68
$Q_{c, max}$ (W)	130

Deep Freeze Temperature= -50° C

Units Req.	2	1	1	1
ΔT (K)	50	40	30	20
R (Ω)	0.77	0.76	0.76	0.76
α (V/K)	0.06	0.06	0.06	0.06
Θ (K/W)	0.78	0.79	0.79	0.79
Q_c (W)	25.00	50.00	50.00	50.00
Q_{pel} (W)	111.24	130.16	67.77	37.45
Q_h (W)	136.24	180.16	117.77	87.45
COP	0.22	0.38	0.74	1.34
I(A)	10.32	11.62	8.36	6.31
Th (K)	273	263	253	243

This module is nothing but TEC1-12715 with a new name. Specifications are almost similar to what we have discussed in the 12715 section. Therefore, even vendor's first choice also reflected the same module that has been shortlisted so far by us.

14. FERROTEC_72001_127_110B:

This module is one of the finest that we have come across so far. This is because of several reasons; first being the temperature difference that it can create and 2nd is the current required to create such a temperature difference is lesser than others, which ultimately means that the power consumed and ultimately the quantum of thermal energy transported to the hot junction side would be lesser than other. The most satisfactory part of this module is its capability to achieve all the temperature difference alone. Apart from that the COP is more than or equal to one in the case of temperature difference of 20 and 30. One more important and positive thing about this module is the heat that it rejects to the hot junction in case of temperature difference of 20. It is by far the least amount of heat that is liberated, in case of 20. Therefore, it has replaced our choice of 12715 and became our primary choice. However, the deal setup and privacy settlement between LG and this vendor would take around 2-3 months. Therefore, we needed to keep our other options open, in case the deal goes beyond the available time limit.

Table 4.17 Performance evaluation of FERROTEC_72001_127_110B

TEM Spec	
I _{max} (A)	11
V _{max} (V)	18.1
ΔT _{max} (K)	83
Q _{c, max} (W)	104

Deep Freeze Temperature= -50° C

Units Req.	1	1	1	1
ΔT (K)	50	40	30	20
R (Ω)	1.15	1.13	1.11	1.08
α (V/K)	0.07	0.07	0.07	0.07
Θ (K/W)	1.20	1.22	1.24	1.27
Q _c (W)	50.00	50.00	50.00	50.00
Q _{pel} (W)	157.45	82.32	50.02	30.62
Q _h (W)	207.45	132.32	100.02	80.62
COP	0.32	0.61	1.00	1.63
I(A)	10.36	7.41	5.8254	4.67
Th (K)	273	263	253	243

15. ETC-128-20-08-E:

Again, this module is capable of handling all the temperature differences. Apart from that heat rejection to the hot junction is also less except from the last module. The maximum heat pumping capacity and current drawing capability of the module is also very high, which makes it possible for the module to draw 50 watts with a temperature difference of 50. This module is now our 2nd consideration after the previously discussed module but the issue of dealing with vendors and getting the module will take a long time followed by series of official processes. Therefore, both recently discussed modules are good but the time of getting is uncertain.

Table 4.18 Performance evaluation of ETC-128-20-08-E

TEM Spec	
I _{max} (A)	24
V _{max} (V)	15.8
ΔT _{max} (K)	71
Q _{c, max} (W)	227

Deep Freeze Temperature= -50° C

Units Req.	1	1	1	1
ΔT (K)	50	40	30	20
R (Ω)	0.49	0.48	0.48	0.48
α (V/K)	0.06	0.06	0.06	0.06
Θ (K/W)	0.51	0.51	0.51	0.52
Q _c (W)	50.00	50.00	50.00	50.00
Q _{pel} (W)	189.04	101.42	56.82	30.38
Q _h (W)	239.04	0.49	106.82	80.38
COP	0.26	0.49	0.88	1.65
I(A)	16.95	12.24	9.15	6.79
Th (K)	273	263	253	243

16. ET-127-20-15:

Table 4.19 Performance evaluation of ET-127-20-15

TEM Spec	
I _{max} (A)	13.1
V _{max} (V)	15.7
ΔT _{max} (K)	74
Q _{c, max} (W)	128.7

Deep Freeze Temperature= -50° C

Units Req.	2	1	1	1
ΔT (K)	50	40	30	20
R (Ω)	0.87	0.86	0.86	0.85
α (V/K)	0.06	0.06	0.06	0.06
Θ (K/W)	0.99	1.00	1.00	1.01
Q_c (W)	25.00	50.00	50.00	50.00
Q_{pel} (W)	81.89	109.54	60.80	35.29
Q_h (W)	106.89	159.54	110.80	85.29
COP	0.31	0.46	0.82	1.42
I(A)	8.17	9.97	7.44	5.77
T_h (K)	273	263	253	243

This module is kind of a smaller version of 12715. Therefore, heat rejection at the hot junction is little lesser than 12715. Alone, it cannot provide a temperature difference of 50, therefore, the use of this module is limited to few cases only or otherwise cascading is to be done.

4.12. Conclusion from the numerical analyses of the module

After going through numerical analyses of the module and considering all the buying options, it was realized that procurement of module from their respective vendors will take almost 3 months, because the security related documentation requires some legal work to be done from both side and this takes time. Different countries and different vendors have different ways of handling their documentation. Therefore, we had to go by such certain steps. Therefore, that idea was dropped for an instant, because of the time issues. Then we jumped on to our primary choice of TEC1-12715. Now there were certain e-commerce platforms from where we could buy the module. Still, there was one was problem which was not solved yet, which was the issue of handling a temperature difference of 50. In the process of finding solution to this we try to search other heavier modules like 19916 but then their cost was approximately 10 times the cost of TEC1-12715. We need to come up with the solution of handling ΔT of 50 with the help of 12715 only. One solution to this problem was to restrict ourselves to lower ΔT , so that we would never have to actually attain a ΔT of 50. But the practical behavior of module at a temperature of -30 was unknown and to create a setup for the refrigerant to flow on the hot side would take a lot of time. Therefore, in the beginning we need to restrict ourselves to the application of water on the hot side for the extraction of heat. Therefore, if a ΔT of 50 can be achieved in case of using water than a ΔT of half of 50 would also be enough for actual practical application. Also, that would be a consideration of factor of safety of 2. Therefore, no we set our primary goal to achieve a temperature difference of 50 by using just water on the hot side of module for the extraction of heat liberated by the module. Now, to achieve this we tried something which is not allowed practically. We did the cascading of modules ourselves. This cascading was not an electrical cascading but more of a practical

cascading. Such cascading is not allowed for several reasons; first being the surface gap that will always going to be there in between the modules, next is the separate power supply requirement for each module. Now, a separate power supply was required for each module because if similar quantum of power supply will be used then heat transported to the base module would be high enough to destabilize the thermal system. In experiments also we come across the problem of overheating of the surfaces. This usually happens when the temperature of the hot side of module usually go beyond the permissible limit. In such cases the module stops working and all the heat start conducting from the hotter surface to colder surface and therefore, the cold surface now gets heated. Therefore, a separate power supply has to be used. In general, the readily available cascaded high cooling capacity modules are stair cased so that no step can consume a power more than the handling capacity of the next step. Such a module is shown in fig. 5.7. But the problem with such module is the effective surface area available for the cooling. Smaller cooling surface area leads to smaller evaporator and also the insulation a stair cased module is difficult. Therefore, we tried to cascade them practically and give separate metered power to each module, so that none of them exceeds the thermal energy handling capacity of the very next module. A 3D model of such an arrangement is shown in the fig. 4.5 below:

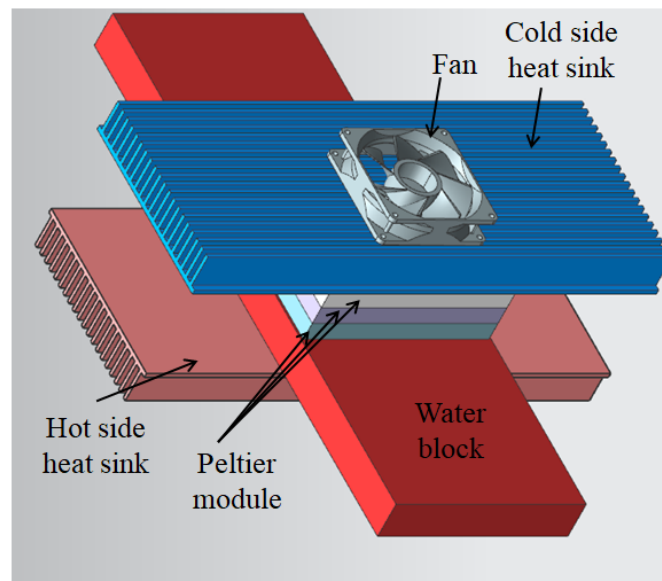


Fig. 4.5 3D model showing the cascaded arrangement of the peltier module

The outer fin sink is used only for the purpose of clamping. Two holes will be drilled from inner in both inner and outer module close to the module so that no bending occurs. This is done because a hole cannot be drilled into the water block because if we do that than there will be leakage of water. The holes on the fin sinks are necessarily required to be drilled closed to module, otherwise a farther hole would cause a bending while tightening of the sinks. A firm tightening is required as discussed in chapter 3. A force of 20 Kg per square inch is required for a good thermal contact of the module with the surface. Therefore, if the holes are farther then there will be bending which

will cause a gap in between the module and surface and therefore, an unwanted thermal resistance will be there, which will be hard to deal with.

From experimental point of view, we ordered two kinds of module; TEC1-12715 and TEC1-12706. TEC1-12710 is used because the heat that it can draw would be easily accepted by the following 12715.

As explained earlier, we decided to go with 2 kinds of modules on the basis of calculative analysis. These analyses included implementation of basic peltier formulae. Also, it was seen earlier during the analyses that a single module of either 12706 or 12715 is not capable of giving desired outcome with respect to ambient conditions. This is because of the desired ΔT , as the desired ΔT is close to 50, therefore, a single module would need to work at its threshold and because of that a very good heat sink is required on the other side. As discussed in the section of reliability, if a module is working on its threshold or peak values then the life of the module decreases. Therefore, it is not desirable to run the module at its peak values, even if the desired ΔT is achievable. Due, to such reasons we decided to go on with cascading of modules, where we intend to place one module over the other in such a way so that the heat side of one will be taken care of the cold side of the other. This approach can help in achieving a higher ΔT and this was also proved, mathematically. On the basis of such proofs, we decided to do several cascading with different ambient conditions to achieve the required ΔT . In any configuration, if we are able to achieve a ΔT of 50 then that can be implemented in the freezer with hotter side being taken care of by the refrigerant.

5.1. List of experiments

The several decided experiments which we conducted with the setup are as follow:

Table 5.1 Experiments conducted for the best module selection

S. No.	Modules used	Thermocouple at cold sink	Thermocouple in box	Fan	Water
1.	TEC1-12706	—	•	ON	Normal
2.	TEC1-12715	—	•	ON	Normal
3.	TEC1-12715 TEC1-12715	—	•	ON	Normal
4.	TEC1-12706 TEC1-12706 TEC1-12715	•	—	OFF	Normal
5.	TEC1-12706 TEC1-12715 TEC1-12715	•	—	OFF	Normal

6.	TEC1-12706 TEC1-12706 TEC1-12715	•	—	OFF	Cold
7.	TEC1-12715 TEC1-12715 TEC1-12715	•	—	OFF	Normal
8.	TEC1-12715 TEC1-12715 TEC1-12715	•	—	OFF	Cold
9.	TEC1-12715 TEC1-12715 TEC1-12715	•	—	OFF	Ice

5.2. Experimental results:

5.2.1. TEC1-12706 with thermocouple in the box

This was the very first test to see the capability of 12706 alone. The main aim was to see what ΔT , one TEC1-12706 will give. Such test would also reveal the practical capability and quality of the bought module. For this test a small fan is used. The fan was directly glued to the heat sink inside the box. It was thought that the fan would suck air directly from the fins and thereby taking the heat away from the air to pump the colder air outwards. But, unfortunately the choice of sink was wrong as the spacing between two adjacent fins was so small such that the humidity within the air freezes in that small are and after some time the whole sink got clogged with ice. Due to this air couldn't flow into the fins anymore. In actual, this realization was achieved after 3rd experiment and therefore, after 3rd experiment we quit on using fan and stick to the sink temperature to see what ΔT can be achieved. This approach was chosen because in commercial refrigerator, it is possible to achieve a temperature equal to evaporator temperature with a difference of 5 degrees. Therefore, further experimentation was done on the basis of such analogy. Also, there is one more problem with the gluing of fan to the sink. There are chances that glue might go into the fins, thereby blocking the fins with glue. At minimum it will decrease the surface area available for air and at worst it will block few fins. Therefore, gluing is not suggested at all for the commercial purposes. The fan glued to the sink is shown in the fig. 5.1 below:

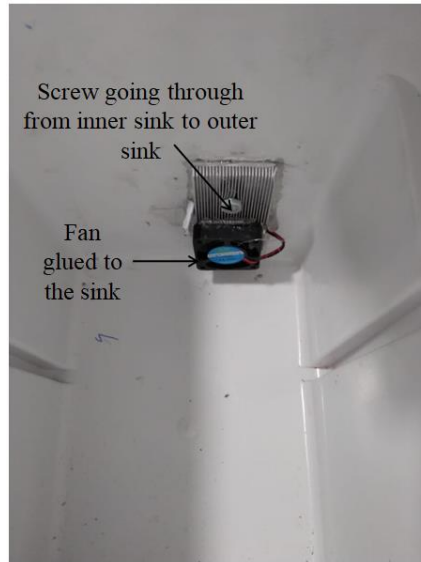


Fig. 5.1 Fan glued directly to the inner sink

One more mistake that was done during the assembly was the use of metallic screw and nut along with washers. Two screws were used and both of them were going inside out and were tightened with the help of nuts and washers. Due to the use of these metallic screws, there was an enormous amount of heat leakage into the box from outside. The leakage was so high that the temperatures of the outside clamped fin sink was also goes down to 12°C , ambient was at 26.4°C . We were aware of this problem from the beginning but still the practical extent was unknown. The outside view of the box with screw nut assembly is shown in the fig. 5.2 below:

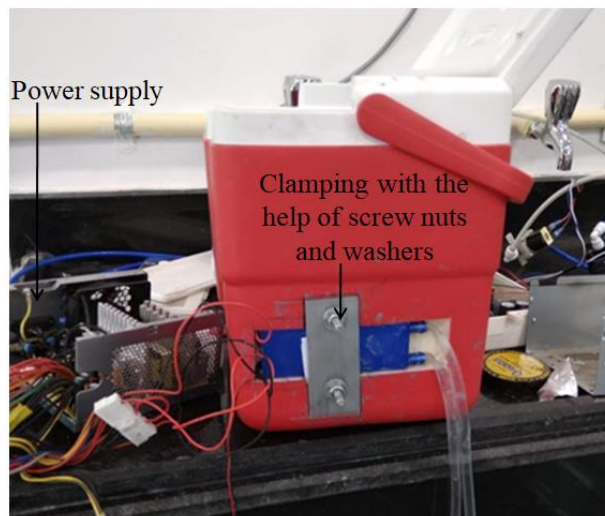


Fig. 5.2 Clamping of peltier module with the box with the help of screws and nuts

This is to note here that the only task of the outside sink is to clamp the whole assembly together. We knew this from the beginning that the screws are going to leak in the heat from ambient. Due to this, the temperature of the sink would go down and as the sink would be in direct contact with the water block heat sink, which is taking away the heat from the peltier devices, the water block would exchange heat with the aluminum fin also. Due to which more amount of heat would go in and to avoid this, a rectangular piece of HIPS was placed in between the aluminum fin sink and water block. The results so obtained from the experiment are given below

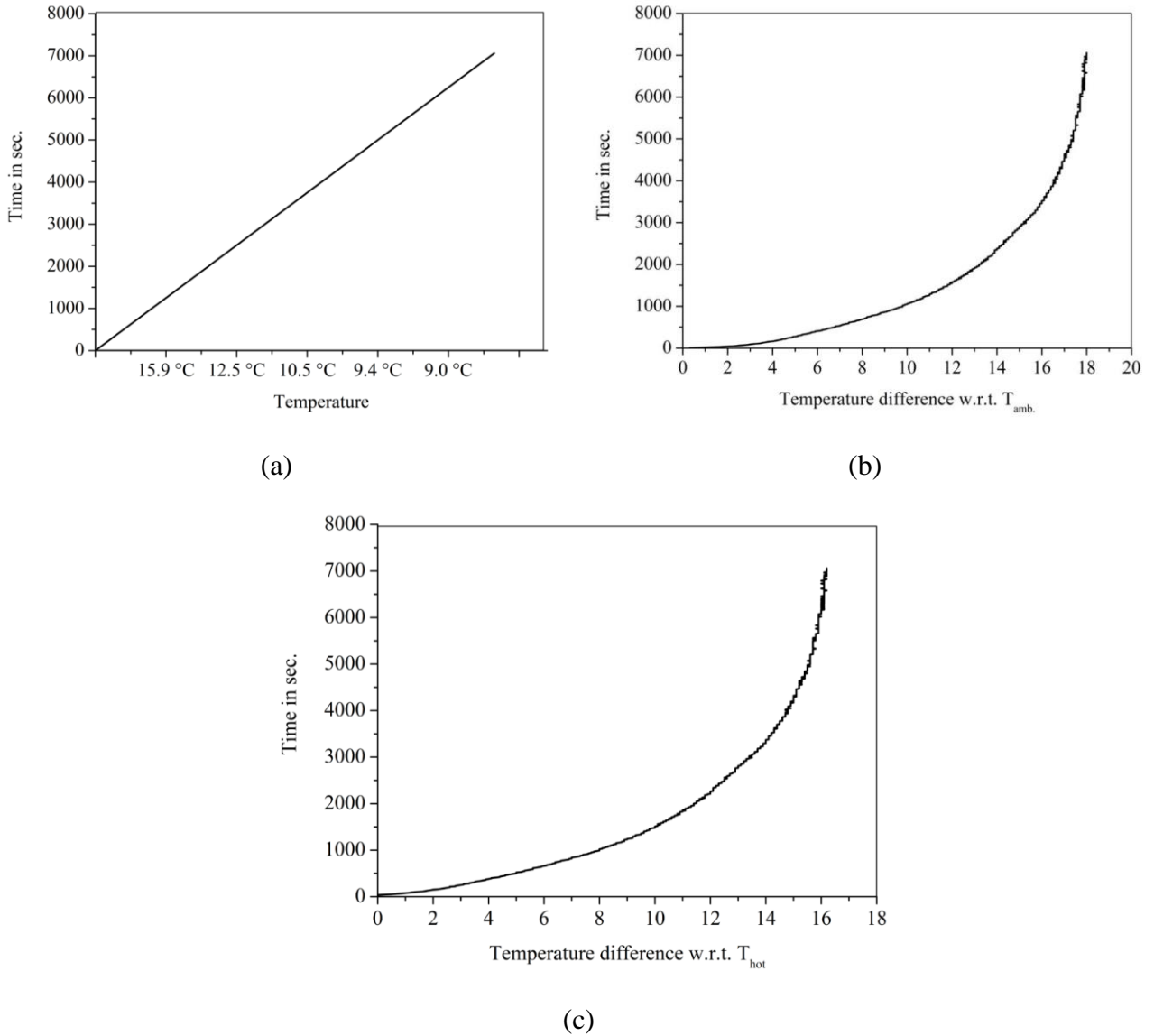


Fig. 5.3 (a) Time vs Temperature_1, (b) Time vs Temperature difference with respect to the hot junction temperature, (c) Time vs Temperature difference with respect to the ambient temperature

Now there are three temperatures, one is the temperature readings given by the thermocouple from the inside of the box, second is the temperature of the ambient and third is the temperature of the flowing water or the temperature of the heat sink. Therefore, we have provided

the rate of change of temperature difference of two differences; one is with respect to flowing water and other is with respect to ambient. Temperature difference with respect to flowing water is already shown above. From the graph it can be seen that the temperature is going down but the rate at which it is going down is very slow. We could have achieved a lower temperature than what we have got here but then that would take a huge amount of time. Please remember that the ultimate goal of having deep freezer is to decrease the time of ice making which is roughly 60 min to 120 min at present in the commercial refrigerators. Therefore, there is no point in taking reading more than 60 min. However, the new desired time for making ice is 10—30 min. Therefore, the desired lower temperature must achieve as soon as possible so as to make the ice sooner.

5.2.2. TEC1-12715 with thermocouple in the box

The problem with using fan and single thermoelectric module has already been discussed but as said earlier the pointless gluing of fan to the sink was realized after 3rd experiment. Just like 12706, we were also keen to see the practicality of 12715. Therefore, in the similar setup we replaced 12706 with 12715. We introduced a duct in this mechanism and the fan was now installed on this duct with a gap in between the fin and fan surface. But still the problem of frost deposition in between the fin spacing couldn't be solved. Frost was still deposited in the fin spacing. After the deposition of frost, the air facing a considerable resistance to go through the fin spacing and therefore, air was entering from the bottom of the duct but was just gliding at the face of the fin and then transported ahead by the fan. Therefore, the problem still persisted. The duct with the fan assembled on the duct is shown in the fig. 5.4, below



Fig. 5.4 Duct with fan

We didn't change the screw mechanism as the new ways of assembling the modules were on the progress but not yet fully achieved. But to avoid the leak as much as possible we cover the extended area of screw with the insulating tape and conducted the experiment. As expected, the results were better than 12706. In fact, it just performed two times of 12706. This is because the temperature that 12706 have achieved in 117 min was achieved in 59 min by 12715, which is almost half and the same is shown in fig. 5.5. After arguing about the fact of not taking readings for longer period, we still stood for 59 min in this case because we wanted to compare the two modules. The changed result can also be due to the introduction of duct with fan. However, later it was realized that due to high resistance to the air due to the deposition of frost, the air was rarely going into the fin and was just gliding on the face of the fin, thereby exchanging very less amount of intermolecular energy with the fin. The evidence of air not travelling within the fin was also the temperature of the box. Until the temperature of the box goes very low, there are no chances for the huge amount of frost to be deposited on the fin. The results for TEC1-12715 are given below

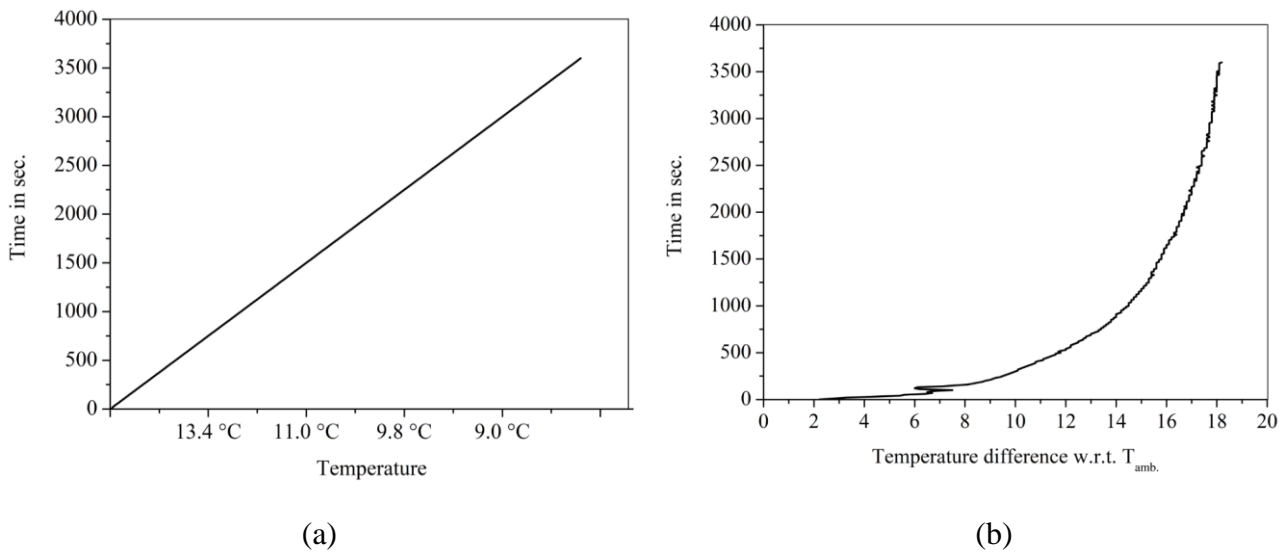


Fig. 5.5 (a) Time vs Temperature_2, (b) Time vs Temperature difference with respect to the ambient temperature

As described earlier and can also be seen from the graph that the time take by this module to bring the temperature of the container down to 8.8°C is 59min, which is almost half of 12706. Next, we will take a look into the variation of ΔT with respect to the hot junction temperature or the temperature of the flowing water.

In this particular graph there is a quick dip after 4 minutes. This happened accidentally, as while taping the box to insulate it, there was an unfortunate disturbance caused to the thermocouple, which was identified on the spot because of the sudden rise in the multimeter reading and therefore, was fixed instantly. However, if one can ignore that fluctuation then a continuous curve can be imagined, which ultimately states that the process remained undisturbed and only the metering device was disturbed.

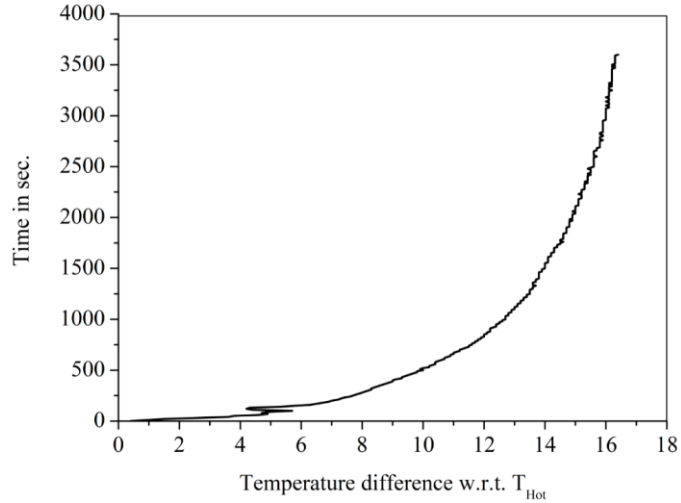


Fig. 5.6 Time vs Temperature difference with respect to the hot junction temperature

Here, the difference is more with respect to ambient temperature than the hot junction temperature. This is because; the ambient temperature was higher than the flowing water temperature. There is a shaky curve at the end in almost all the temperature difference graphs, this is because at the end, the temperature tries to reach stagnancy and therefore, it pivots around the values.

5.2.3. Cascading (TEC1-12715) -(TEC1-12715) with thermocouple in the box

This is for the very first time we have cascaded two modules. Although, this is not allowed technically, because there are readily available cascaded peltier device and one of them is shown in the fig. 5.7, below:

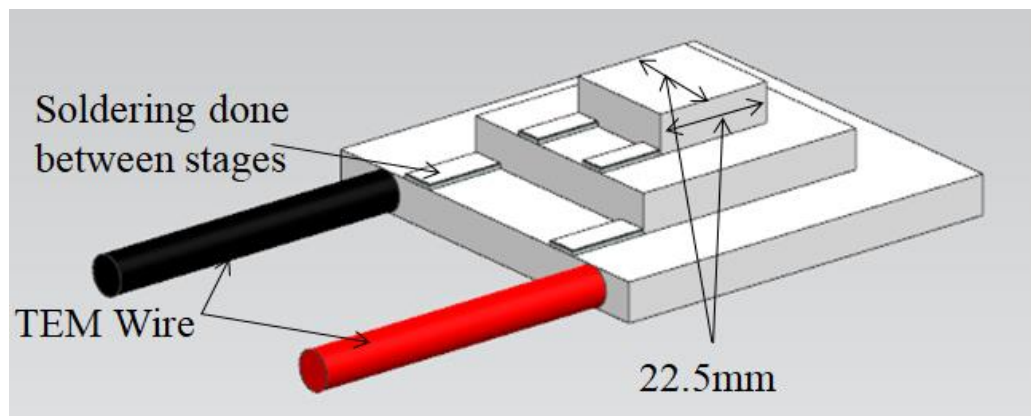


Fig. 5.7 Schematic of readily available cascaded peltier module

Now, the problem with such module is that they have a very small surface area on the top. Even if the module holds the capability of bringing a very high temperature difference, still the place at which this difference will achieve would be very less and therefore, to spread such spotted cooling

within a box is a difficult task. But on the other hand, this is important to understand as why these modules are made like this, in a stair casing manner. This is because when the heat flows down from 1st stage to the 2nd stage, there will be two 2 types of heat that will be transported; one is the heat extracted from the atmosphere and other is the joule effect due to flowing current. Then from 2nd stage to 3rd stage there will be an addition of joule effect of 2nd stage with the heat coming from 1st stage. Just like that 3rd stage will be fully loaded with the heat burden of all the stages above and also its own joule heat due to current flowing into that. Due to such reasons, the stages are made in a staircase manner so that a limited amount of heat can be drawn by a particular stage and also a limited amount of current will be drawn so as to put the final stage to the bottom at ease. So, we in fact tried something similar. We could not compromise the area of the module; therefore, we placed one module over the other and supply only that amount of power which can be hold by the final module. Therefore, separate power has to be sent to the module in order to successfully achieve the stated argument. This requires a special type of electrical circuit so that separate powers can be achieved. This is to not that as both modules now will be individually powered; therefore, different voltages have to be supplied to the module, in order for them to draw different current. This task was achieved using the pc power supply and the image of same is shown in the fig. 5.8, below



Fig. 5.8 PC power supply and its specification

This particular power supply was taken out of a scraped PC. There were few changes done for the experiments to be conducted. These modules are powered with the help of this particular power supply. All the proceeding experiments are all cascading based and therefore, all of them are powered with this PC power supply.

In this experiment, other than fan and cascading of modules, we kept all the settings same. A particular type of fan which has been used by the company in their refrigerators has been used.

This fan is a lot similar to the CPU cooling fan. There is not much information provided by the company except for the RPM, which is nearly 3000. Therefore, the results so obtained in this experiment were thought to be good better than previous because of the inclusion of this fan. However, the dimension of this fan is almost four times the fan used previously. But the problem of frosting still persists in this case also. Then, this was realized for the very first time that the cooling provided by the peltier module is so fast that the humidity nearby the surface is consumed rapidly and also as soon as the air start flowing in, the humidity within the air is also converted to frost. Therefore, the deposition is very quick. After this experiment we were sure of the fact that the chosen fin is not going to work for the air flow and therefore, a more spaced fin has to be chosen. As the size of the module is 40mm × 40 mm, therefore, we first decided to choose a fin of similar size but widely spaced at the same time. One such fin is shown in the fig. 5.9. This fin really has the capability to bring in more air flow but then at the same time it is opened from 5 surfaces. Therefore, only way to place a fan on it is to screw the fan directly on to the top with thick screws. But then the only possibility of choosing the fan is the smaller one which was used in 1st and 2nd experiment. The problem with that fan is the RPM of the fan which was very low such that the time required to cool the box would be high. The fan used in 3rd experiment has the problem of its size which is too huge for this fin and also the design of duct for such a small sink and such a huge fan will not be feasible.

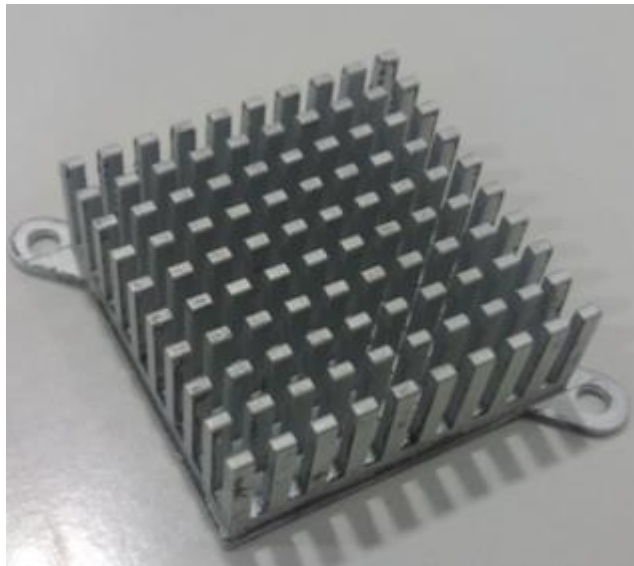


Fig. 5.9 Heat sink suggested in place of the previous heat sink used inside the box

The fan used is shown in the fig. 5.10 below



Fig. 5.10 Fan used for this experiment

The results for this experiment are given below

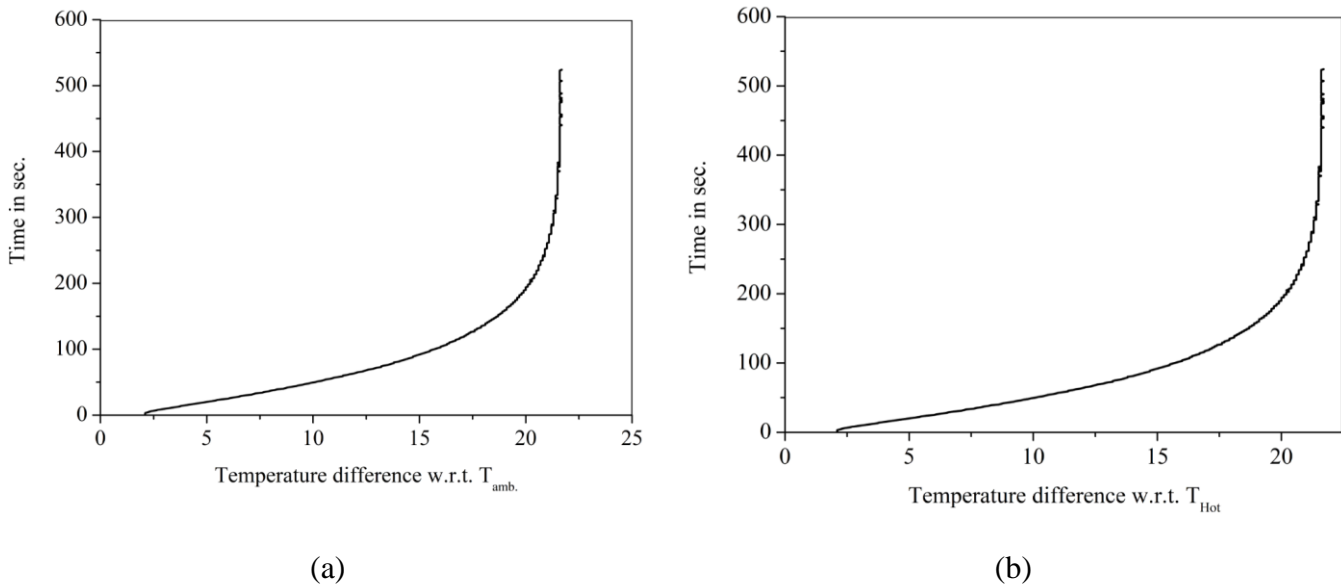


Fig. 5.11 (a) Time vs Temperature_3, (b) Time vs Temperature difference with respect to the hot junction temperature

For the very first time we got some hopeful results which we can appreciate. A temperature of 5.2 °C was achieved just in 6 min and then there was stagnancy and fluctuations about 5.2. Temperature was going up and down about a pivot temperature of 5.2 °C. Therefore, we stopped at 11.4 min. Next, the variations of ΔT with respect to ambient and hot junction temperature are drawn.

This is to note here that a temperature difference of 19.9 with respect to flowing water has been achieved just in 6 min and then there were fluctuations as discussed above. Therefore, we saw some positive attitude in cascading, which we decided to use further. Also, this experiment tells us that single stage modules can be used to cascade into multi-stage module configuration. But then one has to be really careful about using such a manual configuration, because power segregation is must in such case. One similar quantum of power cannot be delivered to each module.

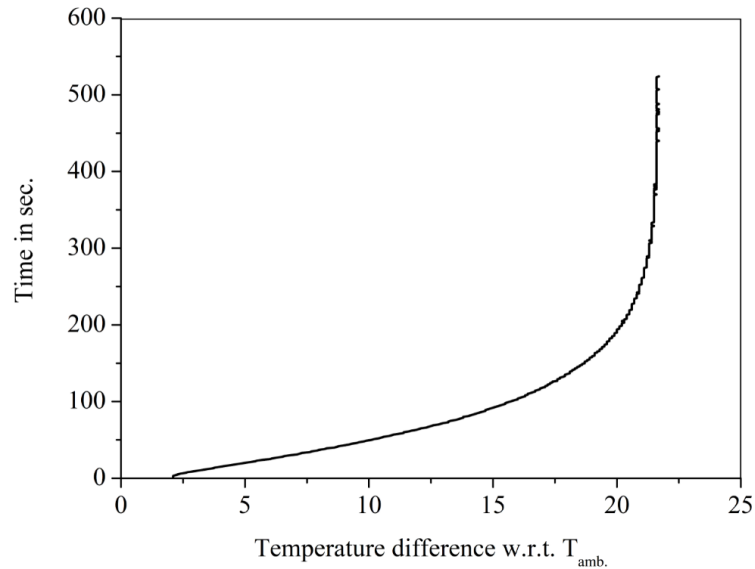


Fig. 5.12 Time vs Temperature difference with respect to the ambient temperature

A temperature difference of 21.7 with respect to ambient was achieved within 6 min. This temperature difference is higher than the hot junction temperature difference because the temperature of ambient was higher than the water flowing in.

5.2.4. Cascading (TEC1-12706) - (TEC1-12706) - (TEC1-12715) with thermocouple on the sink

After performing experiments with placing thermocouples within the box, the readings that were obtained were not going even close to the freezing temperature. Therefore, we first analyzed the problem associated with this. The very first problem that was quite obvious was the narrow spacing within the fin, which easily clogged by the frost deposition. The deposition of frost will be quicker as the better module is used, just like in the case of TEC1-12715. Also, the deposition will be quicker if power near to the threshold value of the module is supplied to the module. This is because then it will try to pump max heat as possible and therefore, frost deposition will be quicker, provided there is a satisfactory setup for heat rejection on the other side. The second problem was with the duct design. An appropriate duct design which will only allow the air to come in from one desired direction following a desired path and then pumping out in a desired manner is required. A work is already going on in deciding the shape of duct and the shape of duct is associated with the third problem, which is the decision of the fan. An appropriate fan which can circulate the air inside the box efficiently and quickly is required. By far, the fan shown above in the fig. 5.10, is best suitable. But there is a problem with the size of the fan, which is too big with respect to size of the module or the fin. There is one more fan which is under survey, this fan is used in few commercial refrigerators of LG and is used for the hygiene filter. This fan will also be tested along with few other options on the table. Currently, the two fans shown above so far are the only fans available in stock. As soon as there will be other fans available, testing will initiate. Therefore, from now on we will be measuring the temperature of the sink. This is done in analogy with the actual freezer

working. In freezers, the temperature within the evaporator is somewhere close to -32°C and the minimum temperature that can be achieved within the freezer is -27 to -28°C . Therefore, a temperature difference of 4 to 5 is there. Therefore, if similarly, if we could achieve the temperature of -50°C on the sink then there is a possibility of achieving a temperature of -45°C . Since, the temperature on the cold side of thermoelectric module is based on the temperature of the hot side of the module, therefore, as lower the temperature on the hotter side, lower the temperature will be on colder side. Therefore, we tried to conduct the experiments even with the water with ice so as to achieve the minimum possible temperature. Within the freezer there is a very cold flowing agent, which is also the primary working fluid in the vapor compression refrigeration system, refrigerant. If we can somehow able to flow the refrigerant on the hotter side of the peltier module then we can achieve a considerably lower temperature on the colder side. Therefore, now the primary goal is the temperature difference that can be achieved on the inner heat sink with respect to the hot junction temperature. Following this lead, the upcoming experiments are all focused on achieving a higher temperature difference. By this stage we were also able to find a solution to the clamping of the module within the assembly. There were few options, like soldering, bonding with epoxy and few others but then the best holding capacity that can be achieved is only through clamping. But clamping with metallic screws was leaking a lot of heat inside the box from the ambient. Therefore, we made 3D printed screws which go all the way inside from both modules. To make the visualization clearer, a 3D model of the whole clamping assembly was made, which shows the stated method in a much clear way. Fig. 4.3, shows the 3D model of the clamping of peltier modules along with water block. The heat sinks are placed perpendicular to the water block. This is because holes cannot be drilled into the water block. The holes drilled in the heat sinks are done very close to the modules so as to avoid the bending of the sink or the water block while clamping. Any bending would cause very uneven pressure on the module and may even result into unwanted thermal resistance. Below is the fig. 5.13 showing the 3D printed screws:

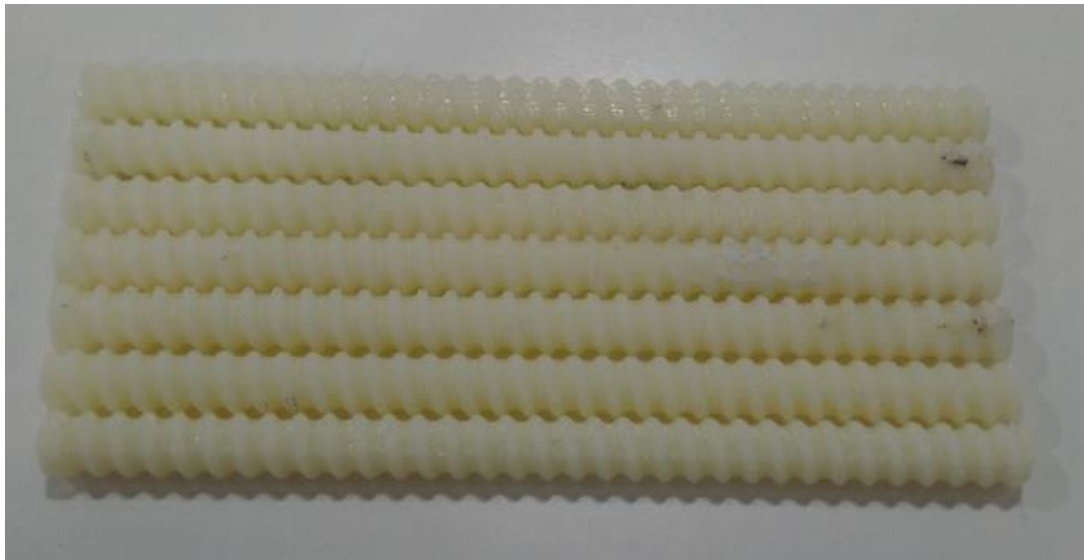


Fig. 5.13 3D printed screws

Nuts for the screws were also made in 3D printing machine but there was problem in thread making, therefore we increased the pitch and thickness, as can be seen in the fig. 5.13 above. Therefore, the issue lies with the holding of the screws at place in a tight position. This was done with the help of HIPS sheet and an adhesive which readily and strongly bonds with HIPS. But to clamp all the pieces together we needed to apply pressure from both sides manually so as to hold the whole assembly together and then we place the drilled HIPS small squares on the cylindrical bars to hold them and at the same time we apply a good amount of adhesive the mating periphery of the screw and the HIPS sheet. We followed this procedure for both sides, inside and outside. The adhesive used is shown in the fig. 5.14 below:



Fig. 5.14 Instant adhesive used for joining HIPS and 3D printed screws

Such an arrangement is shown in the fig. 5.15 below

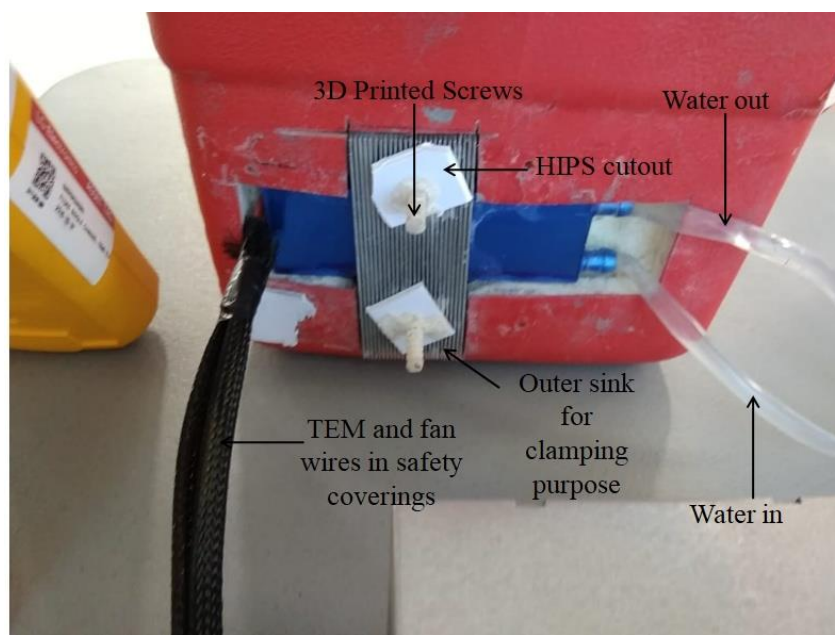


Fig. 5.15 Screw and HIPS pieces joined together

After such an arrangement we performed the experiment and the following results were obtained

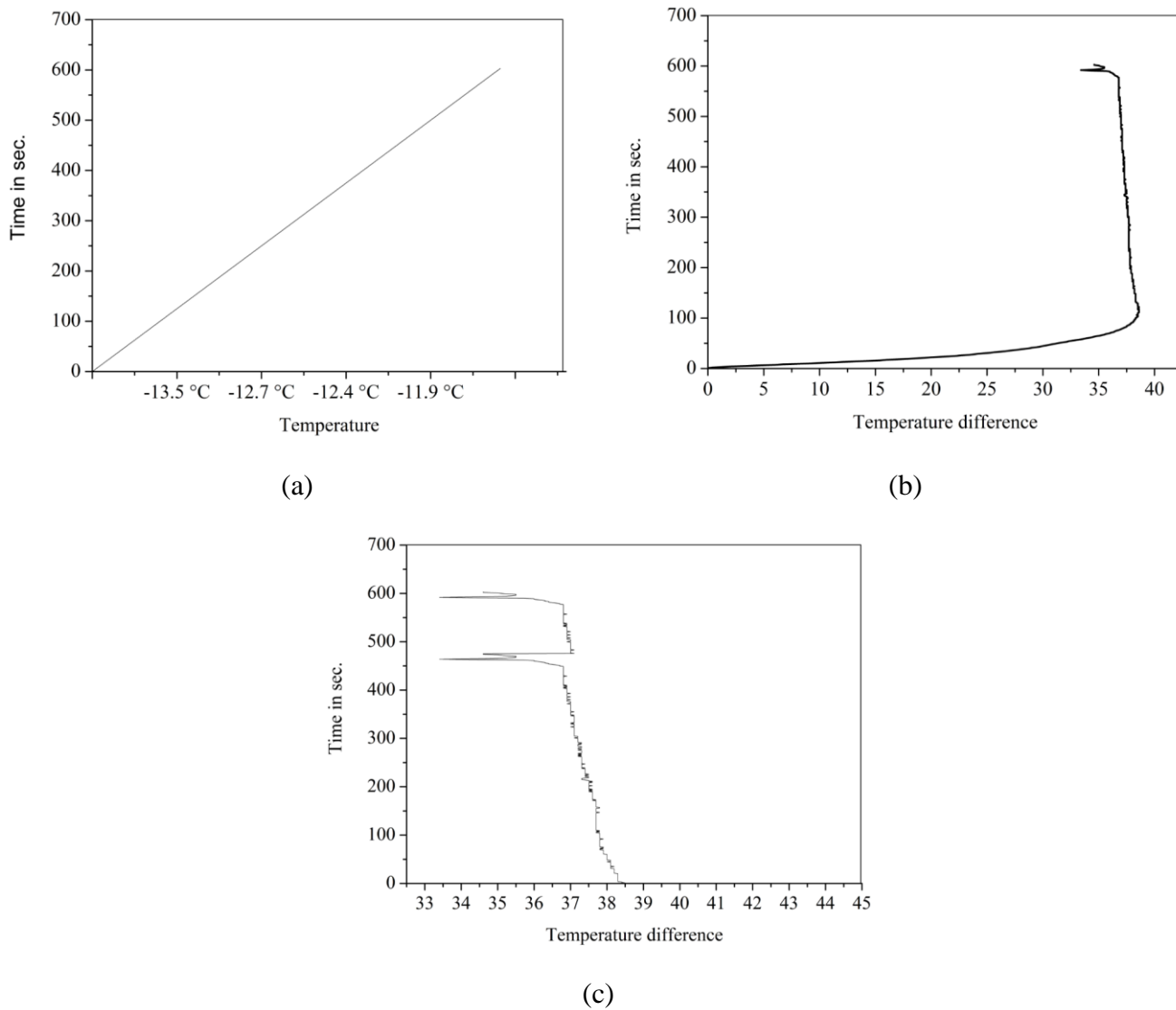


Fig. 5.16 (a) Time vs Temperature_4, (b) Time vs Temperature difference, (c) Time vs Temperature difference_Change in temperature due to sudden shock on the assembly

Fig. 5.16 shows that a temperature of -13.6°C is achieved within 3 min.

Due to sudden shock there is movement of modules within the assembly if they are not tightly assembled and due to that there will be a sudden temperature change and the same is shown in the graph below

5.2.5. Cascading (TEC1-12706) - (TEC1-12715) - (TEC1-12715) with thermocouple on the sink

No doubt the results obtained from previous cascading was good but those results were obtained on the sink and the minimum we touched was -13.6°C . Therefore, in the box, with a nice duct and fan arrangement, we would get around -8.5 . This temperature is not enough to make ice in 10-20 min. Therefore, we needed something more powerful. And that's why, we decided to bring in one 12715 in place of 12706. Therefore, the new arrangement was like 12706 at top then 12715 in the middle as well as at the bottom also. Similarly, like previous cascading, separate power supply is to be given to each of the module and this was done with the same PC power supply. Below are the results obtained with such an arrangement:

Fig. 5.17, gives the variation of temperature and temperature difference with respect to time.

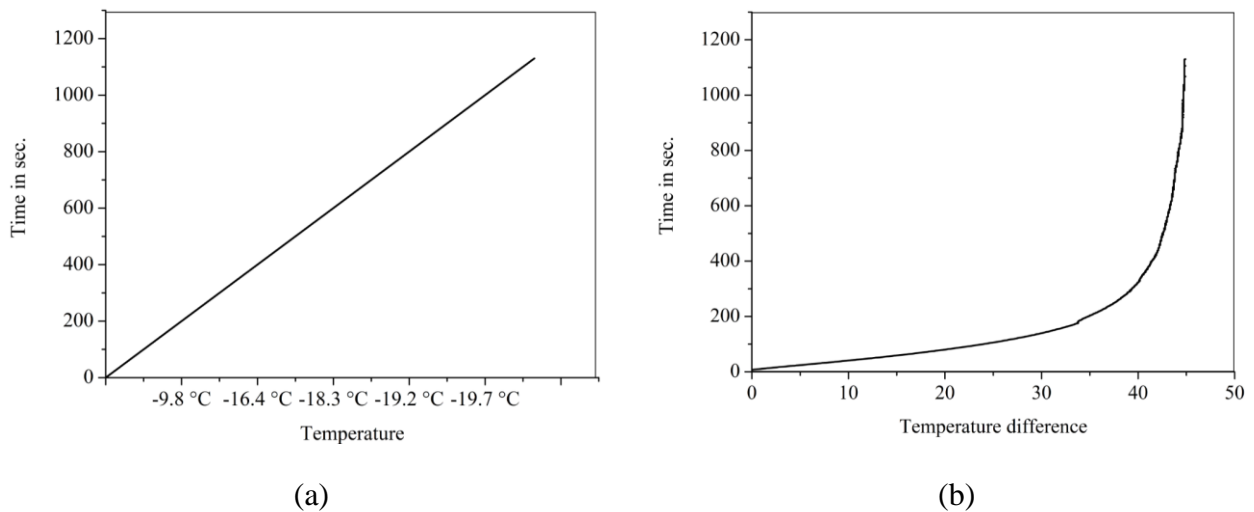


Fig. 5.17 (a) Time vs Temperature_5, (b) Time vs Temperature difference

The results obtained in this arrangement are quite satisfactory to some extent. A temperature of -19.8°C was obtained in 19 min and then it pivoted around this temperature figure. The experiment was conducted for nearly 20 min. There was frost deposition on the surface of the sink more than in previous cases. Also, the clamping held really well throughout the experiment. But still there were doubts related to the thermal resistance. The surface of the sink was now having some scratches due to continuous working with the tools while assembling and disassembling. However, to avoid the effect of scratches, a good amount of thermal paste was used on the surface of the sink so as to make a good thermal contact of the sink with the module. Figure 5.25, shows a temperature reading of -19.8°C on multimeter.

A temperature difference of 44.8 was developed between the two sides of the module. This temperature difference was good in terms of the final application. This is because if we are able to achieve a temperature difference of nearly 45 in the experiments then by taking a factor of safety of 1.5, we may get a temperature difference of 30 which in terms would take us to a temperature

value of -50°C . Therefore, this was for the very first time we were able to claim to perfect possibility of having a separate compartment in the freezer with a temperature of -50°C . But still there is one issue with this result. The time taken by the modules to reach such temperature is nearly 20 min. we wanted to bring it down as much as possible and therefore, we have conducted few more experiments to achieve this.



Fig. 5.18 Multimeter showing a reading of -19.8°C

5.2.6. Cascading (TEC1-12706) - (TEC1-12706) - (TEC1-12715) with thermocouple on the sink and using cold water on the heat sink side

This experiment was conducted with cold water flowing on the hot side of the module. This was done so as to restore the module setting of experiment number 4. This is because 12715 would consume more power than a regular 12706. Also, we wanted to see what effect a cold medium at the hot side would produce on the results. Fig. 5.19, shows the variation of temperature and temperature difference with respect to time.

A very quick result was obtained in the experiment. A lower temperature of -19.6°C was obtained in like 6 min. Therefore, using cold water resulted in a very good result. But we encounter a very unexpected and strange problem meanwhile the experiment. After 7 min there was a rise in temperature which was initially thought of as a fluctuation or pivoting around a value, but after few more minutes this rising continues and rose up to -19.3°C . Therefore, there was a loss of 0.3°C . This loss was there because of the overheating at the module hot side which couldn't be taken care of by the cold water anymore. Therefore, the cold side temperature started to rise up as soon as the overheating occurs. Therefore, this could also occur in actual commercial model. Therefore, we need to perform more experiments to understand this phenomenon more deeply and accurately. The extent of this lowering would define the margin of error that would be there in case of actual model. In actual case, when there will be refrigerant flowing on the hot side of the module, there will be sudden dip and then a rise as well. Therefore, this quantum of rise is important to understand

before implementing this technology in the commercial model. On the other hand, in comparison on experiment number 4, a much lower temperature is achieved.

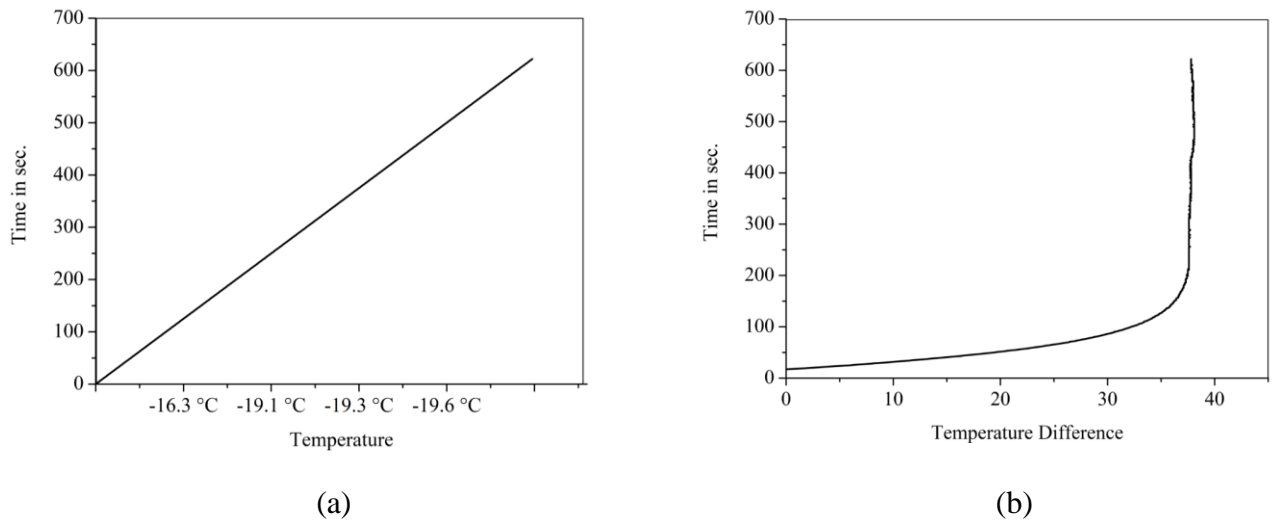


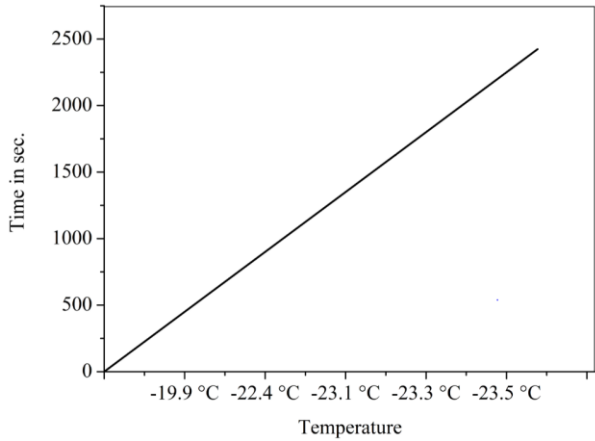
Fig. 5.19 (a) Time vs Temperature_6, (b) Time vs Temperature difference

A ΔT of 38 was achieved in almost 6 min. Therefore, there is not much variation in ΔT in conjuncture with experiment number 4, as there also we have used similar module arrangement. Therefore, by introducing a colder medium on the hot side better results are obtained.

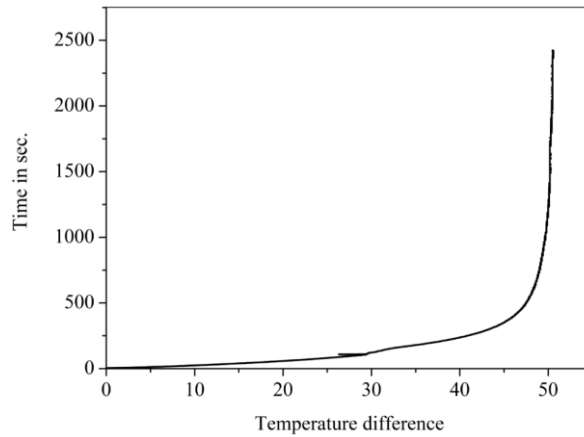
5.2.7. Cascading (TEC1-12715) - (TEC1-12715) - (TEC1-12715) with thermocouple on the sink

After going through such series of experiments, there were two things which were still needed to achieve; first was a lower temperature and more temperature difference and 2nd was to state a restriction the rising of temperature on the module coder side due to overheating on the other side. To rectify these problems, we cascaded only 12715's this time, thereby introducing more power. There is one problem which was evident before conducting the experiment, amount of heat supplied on the hot side of the module. As now there were three 12715's in action, therefore, the electrical power drawn will be more along with the heat pumped out of the box. Due to this the rate of temperature going down would be quick at first and then there will be a sluggish movement because the excessive temperature rises on the hotter side. The problem of temperature rise may also arise. Now, we needed to see what this extra power could give us and the results obtained with this experiment are given below

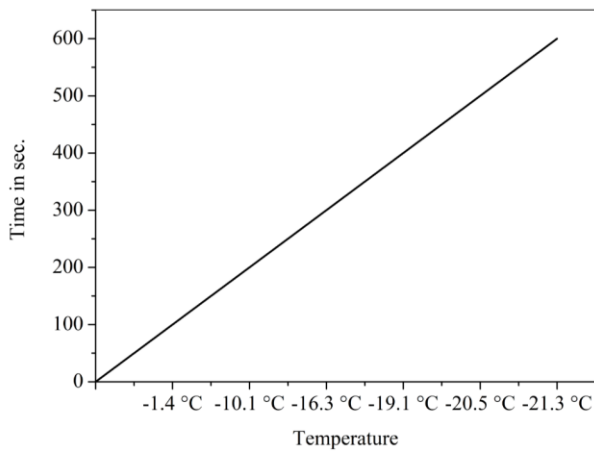
Fig. 5.20, below gives the variation of temperature and temperature difference with respect to time.



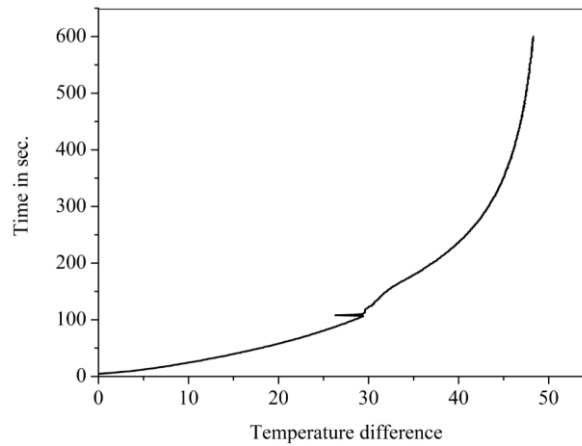
(a)



(b)



(c)



(d)

Fig. 5.20 (a) Time vs Temperature_7, (b) Time vs Temperature difference, (c) Breakout of Time vs Temperature graph for first 10 min, (d) Breakout of Time vs Temperature difference graph for first 10 min

A temperature of -19°C was achieved in almost 4 min and the dipping was still going on. However, the rate of dipping was slow which could be increased by using the colder medium on the other side, which we learnt in last experiment. A lower temperature of -23.6°C was achieved in nearly 40 min. this experiment was continued for long because there wasn't any pivot point achieved till then and we didn't achieve any pivot even at -23.6°C . But then moving this experiment on for more minutes would give us few dips only. As can be seen that -23°C was achieved in nearly 18 minutes. Therefore, this dip of -0.6°C was achieved in next 22 min. therefore, to appreciate this result more let us see what a 10 min progress was. Figure 5.20 shows that a temperature of -21.3°C was achieved in first 10 min and also there is no rise in the temperature even in the full reading of the graph, which was a positive signal in using this configuration of module. Also, a temperature of -19.8°C was achieved in 5 min. Therefore, only a temperature dip of -2.8°C was experienced thereafter. An overall temperature difference of 50.6 was achieved. A dip near 30 is there because there the box was opened and the sink was touched by hand, which causes a little rise in temperature

but everything was back on track as soon as the box was closed again. Below is the fig. 5.21, showing the frost deposited on the sink

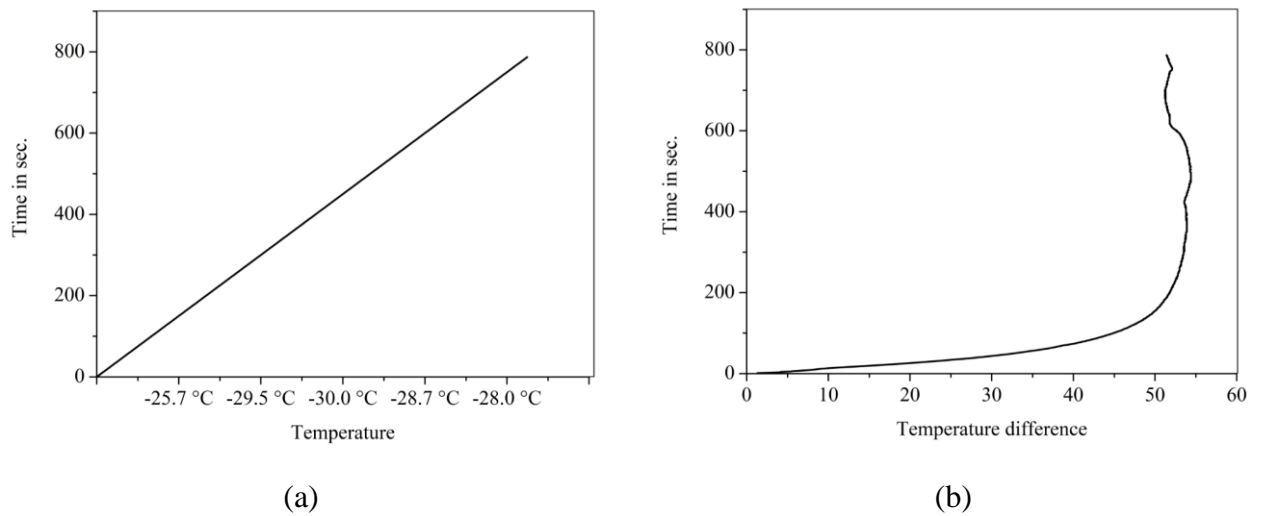


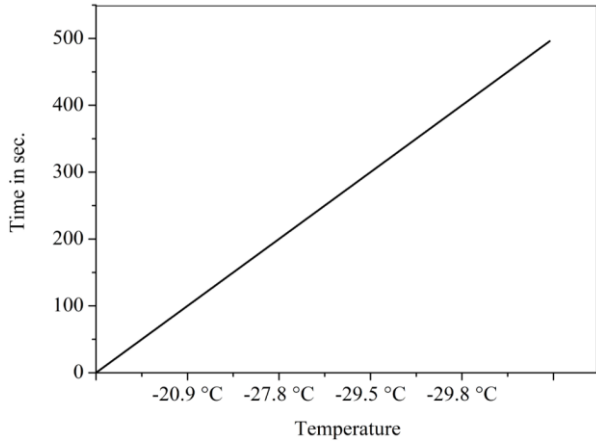
Fig. 5.21 Frost deposited on the sink

5.2.8. Cascading (TEC1-12715) - (TEC1-12715) - (TEC1-12715) with thermocouple on the sink with cold water on the hot side

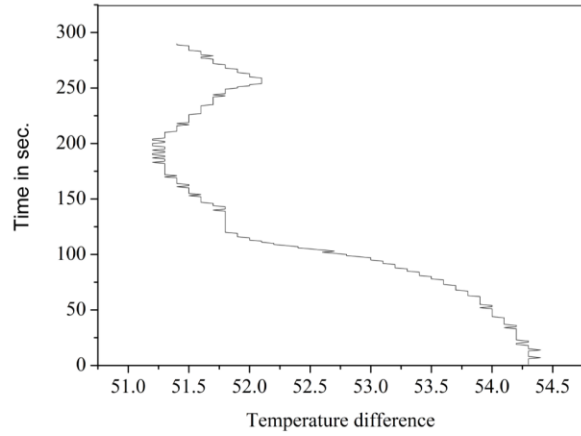
To get the better results of above experiments we introduced cold water on the other side. All the other settings were remaining untouched except the water on the hot side. The results so obtained are given below:

Figure 5.33, below shows the variation of temperature with respect to time





(c)



(d)

Fig. 5.22 (a) Time vs Temperature₈, (b) Time vs Temperature difference, (c) Temperature vs Time till the minimum temperature, (d) Behavioral reversal of TEM in case of exceeding hot junction temperature

A much lower temperature of -30.4°C was achieved in just 16.8min and then there was a temperature reversal. There was a rise in temperature of almost 2.3°C which higher than any experiment above. But just after 27.5°C there was again a rise in temperature until the box was opened. Therefore, that is the point of equilibrium, from where the temperature will slowly rise back again.

The last reading of -27.6°C was counted with the box opened. Therefore, in this particular arrangement a dip 2.3 is there. If we compare this with the dip achieved in experiment number 5 then we can say that as higher module is chosen, more amount of rise will be there. Figure 5.34 shows a minimum dip if -30.4°C is achieved in 16.8 min. However, we have faced a module behavioral reversal, but still the temperature difference achieved here is quite significant, 54.4. This figure was achieved in nearly 17 min.

Figure 5.22 (d) shows the behavioral reversal of TEM in case of exceeding hot junction temperature. Although, there is a behavioral reversal in this case, but still the things stayed up 50 in terms of temperature difference. Therefore, this configuration of modules is the best suited for the desired results. Multimeter showing a reading of 31.6°C is shown in fig. 5.23. Such readings were achieved after we kept it going for little longer:

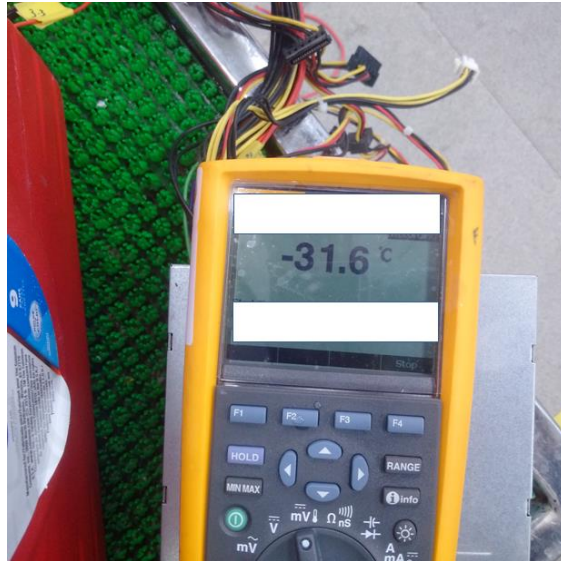


Fig. 5.23 Multimeter showing a reading of -31.6°C

5.2.9. Cascading (TEC1-12715) - (TEC1-12715) - (TEC1-12715) with thermocouple on the sink with significant colder water on the hot side

This experiment was conducted so as to reach the lowest possible temperature and the temperature difference as well. The aim was to achieve a temperature of -35°C just by using water. So, if we were able to achieve this then even a temperature of -50°C can be achieved very easily by just flowing refrigerant on the other side.

A temperature of -35°C is very low and therefore, a significant sealing of the box is required. This is because any amount of heat inflow would not let us achieve the desired temperature. To conduct several experiments on the same box, there were number of holes and cuts on the box. Such openings were taken care of in previous experiments also with the aid of insulation paper tape. But for this specific experiment we wanted to take the insulation to one step higher and therefore, we have used the silver insulation tape to insulate the box from the ambient. The box with insulation is shown in the fig. 5.24 and fig. 5.25, below:



Fig. 5.24 Front view of the box



Fig. 5.25 Back view of the box

The results obtained with an arrangement are given below

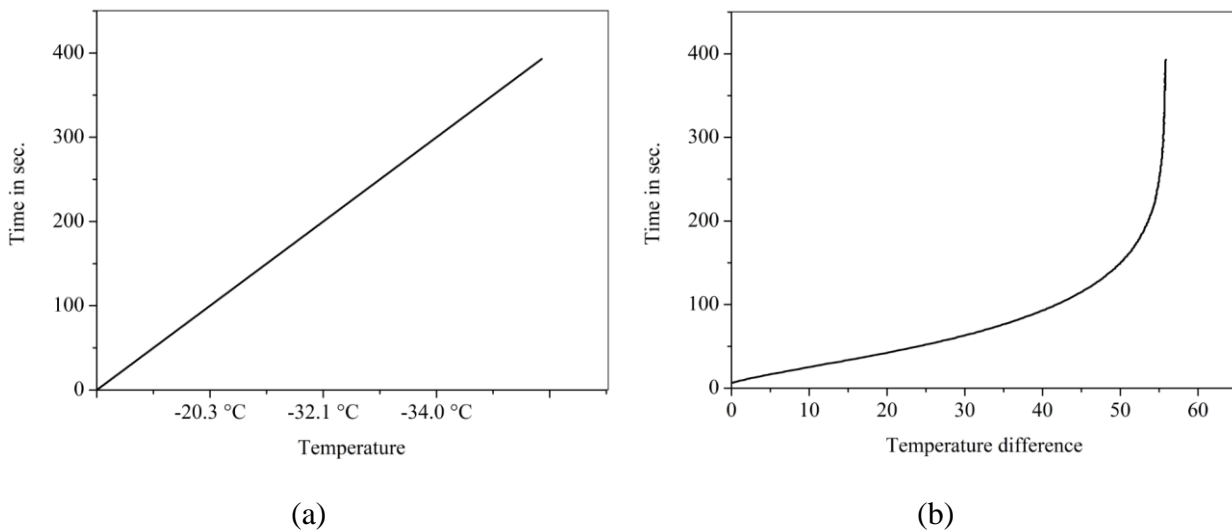


Fig. 5.26 (a) Time vs Temperature_9, (b) Time vs Temperature difference

A temperature of -35.5°C was achieved. However, due to glitch in the multimeter, no readings were stored after -34.4°C . Such a temperature was achieved in less than 8 min, which was the most groundbreaking result for us. This was for the first time we beat the conventional evaporator in terms of temperature achieved, because the temperature of evaporator goes up to -32°C .

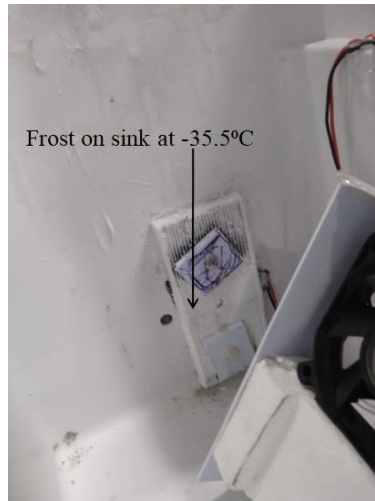


Fig. 5.27 Frost deposited on the sink

A temperature difference of 55.9 was achieved within 7 min. this was the most satisfactory result that we have achieved so far. Also, the temperature was continued for longer and there was no reversal, this because a significant colder water was being transferred on the hot side of the temperature. The frost deposited on the fin was really dense and the image of the same is given in the fig. 5.27.

In the figure 5.27 above, it can be seen that we have also been working hard on duct and fan. The duct and fan shown in the figure is supposed to show much better results. However, the main problem lies with the sink and therefore, a proposal of using new sink has been given and selected sink is shown in the fig. 5.28 below



Fig. 5.28 Image of the new selected fin

The multimeter showing a reading of -35.5°C is shown in fig. 5.29 below:



Fig. 5.29 Multimeter showing a reading of -35.5°C

In this chapter, we will try to conclude from our understanding from the last 5 chapters, specifically from the experimentation. We will also try to point out several important points that need special attention while handling thermoelectric module.

6.1. Installation

The installation of peltier module is the one of the most crucial part. This is because, we had our modules cracked while installation, also the wires of one module broke down from the joining because of excessive pressure placed on close to the soldered junction, metallic screws caused enormous heat leakage from the ambient, 3D printed screws were hard to build with standard thread dimensions as the threads wear off in just one time screwing, permanent joining method of the modules must be avoided and wires must not be packed firmly such that heat transfer out of the wires become dull, this is because the wires of modules are very thin and therefore, a long running process may cause excessive heating.

6.2. Power supply

We have used here a PC power supply, because three modules were needed to be powered differently at instances. But this method of giving the power is not the best one. A circuit is required for the cascading purpose which must be capable of providing separate power supply.

6.3. Temperature difference

We have used modules whose size is 40mm × 40mm, which is not very huge as compared to the size of the evaporator. But still, we were able to achieve a temperature of -35.5°C on the surface of such module and this temperature was reached just in 7 min. therefore, cooling with the help of peltier module is quite a possible task, however, maybe inefficient. Also, a temperature difference of nearly 55 was achieved during the experiments and this was achieved by having chilled water on the other side. Now, one can think of the possibilities of achieving -50°C or -60°C if refrigerant can be provided on the other side.

6.4. Heat sink

One of the biggest problems with the peltier module is the heat liberated by the module during its working. If a substantial amount of heat is to be pumped out of the module then that would require a higher amount of current this would lead to very high heat generation due to Joule effect. Therefore, the hot side of the module must be taken care of perfectly according to the application; otherwise, a reverse effect in the behavior can occur.

6.5. Insulation

Insulation around the module must be done to prevent any leakage of heat. Insulation is crucial in case of thermoelectric module because the modules are very thin and therefore, the hot side and

cold side are not too far away from each other. In our case we have cascade the modules, therefore, distance between hot and cold side increased and there was enough space to place EPS foam in between.

6.6. Module type

The type of module chosen is important in two terms; one is the heat pumping capacity of the module and other is the sealing of the module. First one has been discussed enough in several chapters within the thesis. However, second one is important if the cooling is done below freezing, because in such case there will be a chance of frost deposition and deposition of frost within the module will increase the resistance and affect the performance. Therefore, a sealed module must be used in case of cooling below freezing.

6.7. Future Work

The final aim of the proposed project is to create a separate zone within the freezer which can give a temperature of -50°C . This exact couldn't be accomplished at present because of unavailability of several components and few manufacturing glitches. Therefore, we decided to achieve a very similar result in relation to the primary aim. If the primary aim is to be achieved then there will be a flow of refrigerant on the hot side of the module and the temperature difference achieved would be nearly 20. This is because the temperature of evaporator is nearly -30°C and therefore, if we can achieve a temperature difference of approximately 50 and a temperature of nearly -30°C then there will be an absolute possibility of achieving of a desired lower temperature. Temperature difference of 50 is decided, because if a temperature difference of 50 is possible at -30°C then the even the half temperature difference can be achieved at -50°C , which would be a factor of safety of 2. However, the prototype made was keeping the main aim in mind. Therefore, our prototype fits perfectly in the freezer compartment of an LG ALPHA refrigerator. Below is a fig. 6.1, showing LG ALPHA refrigerator.



Fig. 6.1 Alpha refrigerator of LG

As can be seen from the fig. 6.2, above, that an ALPHA refrigerator is a very huge machine and therefore, such an expensive utility, deep freezer, is decided first for this huge refrigerator. Below is a Fig 6.2, showing the freezer of this ALPHA machine:



Fig. 6.2 Freezer compartment of an ALPHA refrigerator

The space realization of this freezer may not be intuitive. Therefore, we installed our prototype within the freezer to see if it actually fits within the freezer. However, this wasn't any hit and trial, we bought a box by deeply looking into the size such that it can fit perfectly in the freezer. There are grills given in the freezer which circulates air in the freezer if box is placed right in front of the freezer with certain openings matching the grill then the temperature of the box will always be at freezer's temperature, until the modules are not powered. As soon as the modules are powered the temperature of the box will go down than that of the freezer. But then at the same time if the openings to the grills are opened then heat will sneak into the box continuously, therefore, certain arrangement has to be done so that openings to the grills will be closed as soon as the modules are powered in. For than an inspiration from the working of heart is taken and an idea of using something similar to pulmonic valve is proposed and a schematic of same is given in fig. 6.3, below:

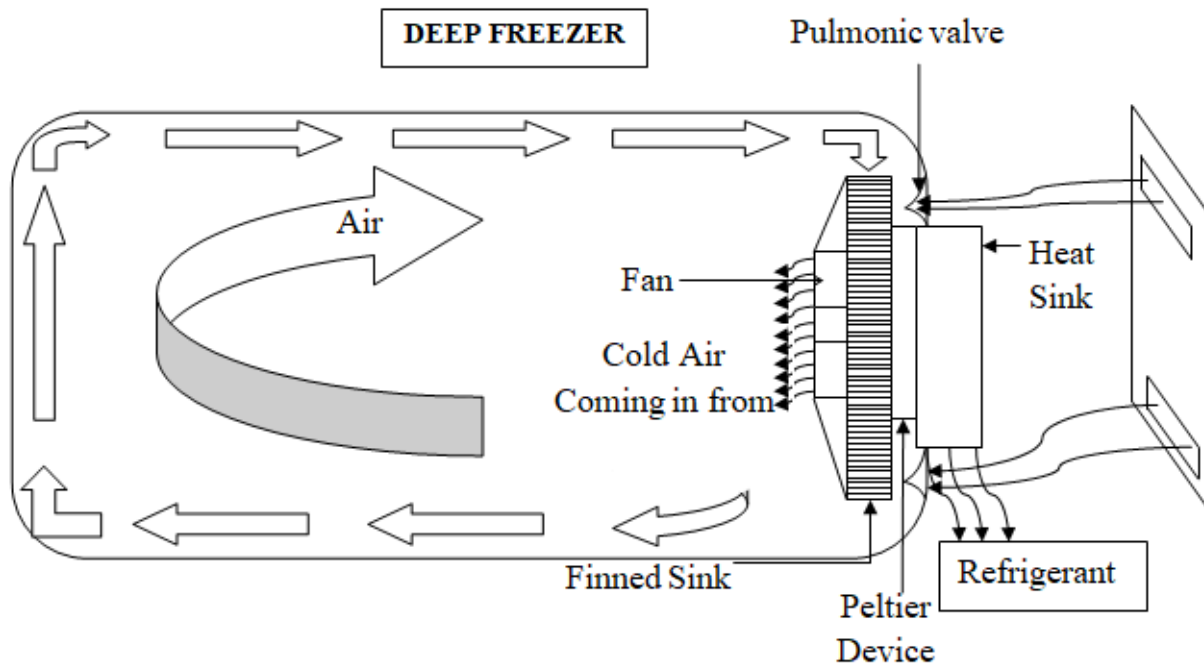


Fig. 6.3 Schematic showing the Deep freezer incorporated with pulmonic valves at the grills

This is proposed as one of the works that can be done to make the product more robust.

Apart from this, facilitating refrigerant on the hot side of module is going to be the second work that can be done in future. For that, the box has to be placed within the freezer and some changes has to be done in the evaporator or maybe a new line can be drawn out of the throttling device to the hot side of the module, and that line may be controlled by a solenoid operated valve such that the line will only be active if the deep freezer is switched on. Below are the figures, fig. 6.4 and fig. 6.5, showing the box placed in the freezer.



Fig. 6.4 Box placed in the freezer of alpha refrigerator

The box fits perfectly in the lower compartment of the freezer.



Fig. 6.5 Perfect match of the box with the space provided in the freezer

Box is not hindering the air ducts placed at the freezers bottom at the entry. Also, the box size does not hinder the door closing. The depth of the box is quite enough to reach the grills at back and it also stay intact with the front so as to have the easy accessibility.

Therefore, the only work left is the testing with the refrigerant on the hot side of the module and this can be done in future so as to come up with a commercial product.

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