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Thermoelectrics for Cooling Power Electronics

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Michael Ralf Starke

August 2006

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Dedication

To My Family and Friends

Acknowledgements

There are a good number of people that I would like to thank in assisting me in completion of my thesis. First, I would like to thank my advisor, Dr. Leon Tolbert not only for supporting me financially, but also for his advice and guidance in obtaining my degree.

I would also like to thank my committee members, Dr. Jack Lawler and Dr. Fangxing Li, for their helpful suggestions.

I would like to provide a special thanks to Curt Ayers for providing this thesis topic and giving me plenty of time to put this thesis together. I would like to thank all of my peers, Joe Barnes, Tim Buress, Pierre, Boheme, Gerry Callison, Eric Cardwell, Weston Johnson, Fasil Kahn, Surin Khomfoi, Luttrell, Pankaj, Pandit, Nirajan Patel, Chris Patton, and Ben Sooter not only for helping me with school related work, but also for providing ample opportunity to have fun.

Last, I want to make a special note to those at the NDC whose influence helped me grow as individual, Tim Elliot, Abby Kye, Sandy Luttrell, Mandy and Hollie Preston, and Eric and Kim Talyor.

Abstract

To increase the efficiency and reduce emissions, the hybrid electric vehicle (HEV), fuel cell vehicle (FCV), and electric vehicle (EV) types were developed. All these vehicle types rely on power electronics (PEs) to function. Yet, the reliability and performance of PEs are directly related to the operating temperature. Therefore, cooling is considered an option to reduce the operating temperature.

An examination of multiple cooling methods including conventional cooling, direct and indirect cooling, and spray cooling shows that the use of thermoelectric (TE) modules has multiple justifications including reliability, thermal control, operation in harsh conditions, and the non-application of refrigerants. Nevertheless, the coefficient of performance (COP) of TE devices falls heavily with large ΔTs.

To meet the demands of cooling PEs with a large ΔT, layering TE modules must be performed. Although a minimum application of several layers can be performed, increasing the number of layers from the minimum demand results in an increased COP.

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Chapter 1

INTRODUCTION

Concerns over the environment and energy consumption have placed an emphasis on the development of new more efficient and less pollutant technologies. This has been particularly true for the automotive industry. Automobiles have been accused of being one of the leading sources of global warming, acid rain, and lung related health diseases including cancer and asthma. In an effort to reduce automobile emissions, automobile manufacturers and the government have conducted large amounts of research into the use of advanced technologies [1-2]. One of these advanced technologies is the thermoelectric (TE) device. Current research into this device involves cooling automotive components and power generation.

1.1 Power Electronics

Several types of vehicles are under investigation to reduce pollution and increase efficiency, the hybrid electric vehicle (HEV), the fuel cell vehicle (FCV), and the electric vehicle (EV). Although these three vehicle types have varying energy sources, one element that these vehicles have in common is the use of power electronics (PEs). The PEs in these vehicles convert the electrical power supplied by the energy source to the appropriate power type to propel the vehicle. Hence, it is mandatory that the PEs function efficiently and reliably [1-2].

Currently, most PEs are made of Silicon (Si) which has a reported breakdown temperature due to packaging of approximately 120 ^{o}C [3]. However, this temperature limit is often exceeded in the normal operation of HEVs, FCVs, and EVs. With HEVs, the PEs are commonly located in proximity of the internal combustion engine (ICE) to reduce transmission losses. Here the temperatures tend to be much higher than the 120 ^{o}C limit imposed by the packaging of Si. As a result, PEs can fail without proper temperature controlling measures. Even without the ICE as in the case of FCVs and EVs, PEs must handle large amounts of power and due to losses can produce substantial amounts of heat. To combat these high temperatures, several solutions are presented [1-2].

One solution is to replace Si with Silicon Carbide (SiC). SiC is capable of operating at much higher temperatures without breaking down and lower on-state resistance. SiC devices also have higher thermal conductivities. This allows SiC to release the heat at a quicker rate to the surrounding environment. Regardless of the benefits, SiC PEs are currently too expensive and not yet mass produced [4].

A second solution is cooling. Cooling the PEs affords several benefits. First, the PEs can be placed in any temperature environment as long as the PEs acquire acceptable cooling. Second, the PEs can be utilized under higher power conditions. This grants the PEs the potential to function at peak conditions longer without suffering from thermal breakdown. Hence, through cooling, increased performance and higher reliability can be expected from the PEs.

1.2 Cooling Techniques

To maintain optimal performance of PEs and prevent premature failure, adequate cooling is critical. Cooling techniques are usually classified into two groups, conventional and advanced cooling. Conventional cooling techniques commonly consist of forced air or natural convection and conduction. Advanced cooling techniques are comprised of new technologies and methodologies such as direct and indirect cooling, spray cooling, and cooling through the use of TE devices [5].

1.2.1 Conventional Cooling

Conventional cooling employs large heat sinks and fans as a means to cool. The reward from this type of cooling is simplicity. The PEs are attached to a heat sink with high thermal conductivity and fins as seen in Figure 1.1. The heat sink provides the expeditive absorption, transferal, and removal of heat from the PEs. To boost the efficiency in the convection process, a fan is employed to circulate air along the heat sink fins. Increasing the cooling capacity of this system is as straightforward as intensifying the airflow either by obtaining a larger or higher-speed fan. The drawbacks to such a design are the low heat flux removal capacity, the development of hot spots, and the difficulties imposed by maintenance [6].

In the conventional cooling system, the heat is in effect directly transferred from the PEs to air. Air has a poor thermal conductivity, therefore limiting the heat flux removal capacity. This is the principal reason for the application of heat sinks. Heat sinks absorb the thermal energy from the PEs much more readily than air and distribute the heat through the use of fins that deliver large surface areas for convection to air [5, 7].

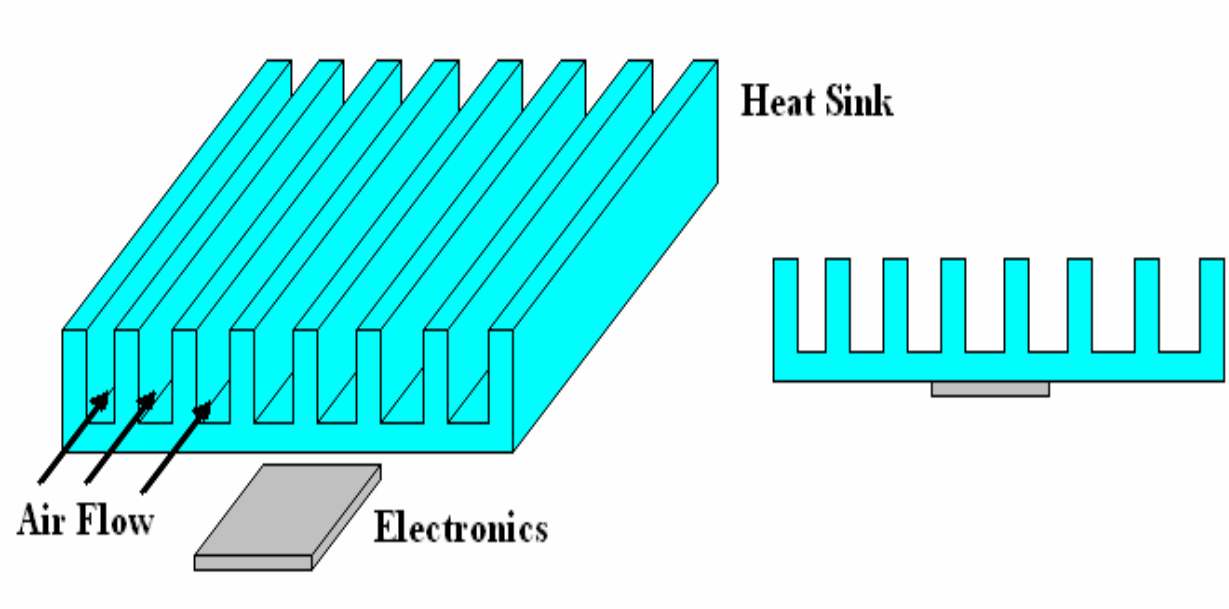


Figure 1.1. Conventional cooling.

Due to the small size and resulting limited surface area of PEs, hot spots can generate at solder locations. The heat sink cannot make contact with the solder; hence cooling is not rendered to these locations. These hot spots can spur the growth of cracks and voids between the PEs and their interfaces and ultimately to the deformation and failure of the power electronic modules [5, 8].

Since a fan is a dynamic component, maintenance is also a concern. Should the fan malfunction, the efficiency of the heat removal system would fall dramatically. This drop in cooling could elicit the overheating and failure of the PEs [5].

1.2.2 Advanced Cooling

As aforementioned, direct and indirect cooling, spray cooling, and the use of TE devices are classified as advanced cooling techniques. Direct, indirect, and spray cooling all adopt liquid as the cooling agent. TE devices do not draw on any form of cooling agent, but instead rely on several physical phenomena to cool.

1.2.2.1 Direct and Indirect Cooling

Indirect cooling uses a liquid as a cooling agent but does not permit the direct contact of the cooling agent and PEs. Instead, a thermal pathway, usually a metal with a high thermal conductivity, is furnished between the PEs and the cooling agent as seen in Figure 1.2. The benefits to indirect cooling relate to the cooling agent. Since the PEs do not come in contact with the cooling agent, the cooling agent can be any liquid. Water is the most commonly applied cooling agent in indirect cooling applications, thanks to its

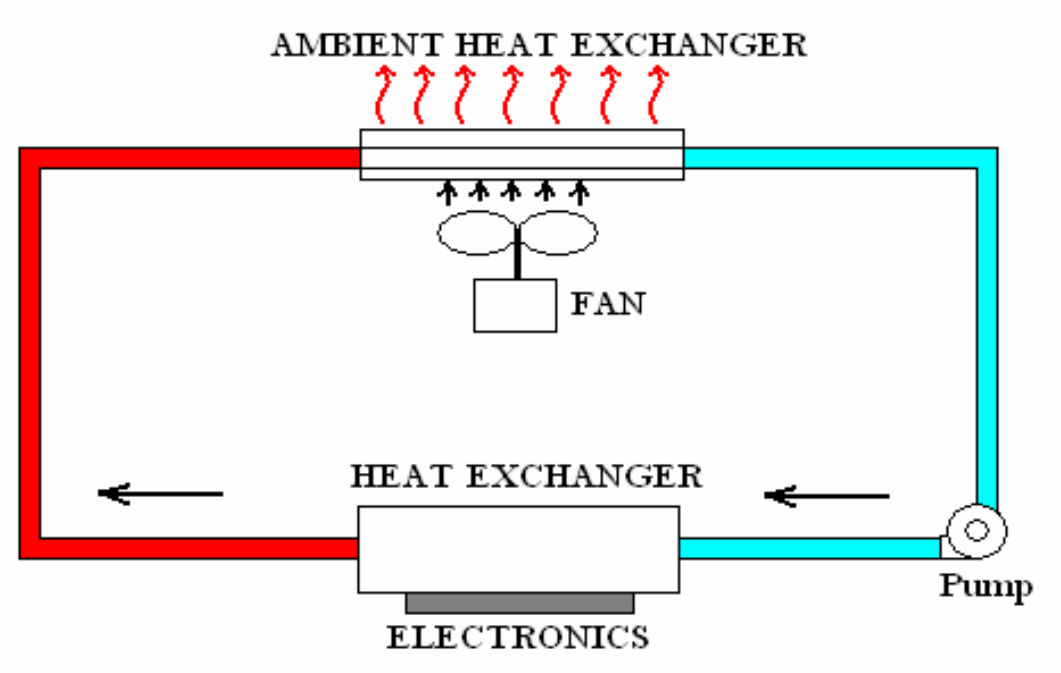


Figure 1.2. Indirect cooling.

high thermal conductivity and environmental compatibility. The heat flux capacity of indirect cooling exceeds that of conventional cooling by a great margin as a result of the high thermal conductivity of water [9-10].

Unlike indirect cooling, direct cooling actually submerges the PEs in the cooling agent as seen in Figure 1.3. The lack of separation between the cooling agent and PEs allows for two-phase cooling. Two-phase cooling exploits two phases, liquid and vapor, to remove heat. Essentially, the PEs create a temperature gradient at the surface of the PEs within the cooling agent. The temperature rises from the heat produced by the PEs until the cooling agent begins to boil and convert to vapor. Once in vapor form, the vapor begins to rise due to buoyancy removing the heat from the PEs. As the vapor reaches the ambient surface, the vapor commences cooling. Finally, the vapor returns to the liquid

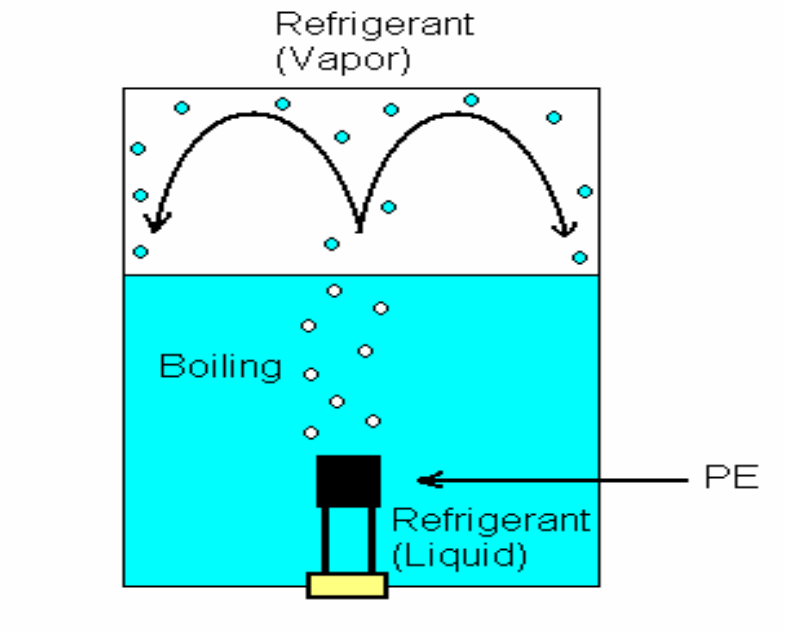


Figure 1.3. Direct cooling.

phase completing the cycle.

Two-phase cooling enables direct cooling to have a much greater overall heat-transfer coefficient compared to that of indirect cooling. Therefore, direct cooling is capable of removing larger quantities of heat from a smaller volume. This gives direct cooling a distinct advantage over indirect cooling and conventional cooling in terms of cooling capacity. Direct cooling also does not suffer from hot spots since the entire circuit is submerged and is cooled. However, in order to use a cooling agent for two-phase direct cooling, the cooling agent must have a high dielectric strength, be non-corrosive, and have a normal boiling point within 20-80 ^{o}C [6, 9-10].

1.2.2.2 Spray Cooling

Spray cooling, as the name implies, injects cooling agent through nozzles onto the PEs module as seen in Figure 1.4. The liquid droplets impinge on the surface and form a thin liquid film. Similar to direct cooling, heat from the PEs initiates boiling, which leads to evaporation of the cooling agent. The constant impingement by the spray forces convection of the cooling agent and contributes to cooling the PEs. The hot liquid and vapor cool in the ambient container and returns to the reservoir via a drain to repeat the cycle. The cooling agent frequently employed is water that is subcooled or at saturation temperature to provide more effective cooling. A thin protective layer is coated onto the PEs to protect against short circuits because water has a very low dielectric strength.

The asset of this type of cooling is the large heat flux capacity. Water as noted earlier has a large thermal conductivity allowing for considerable heat flux capacities.

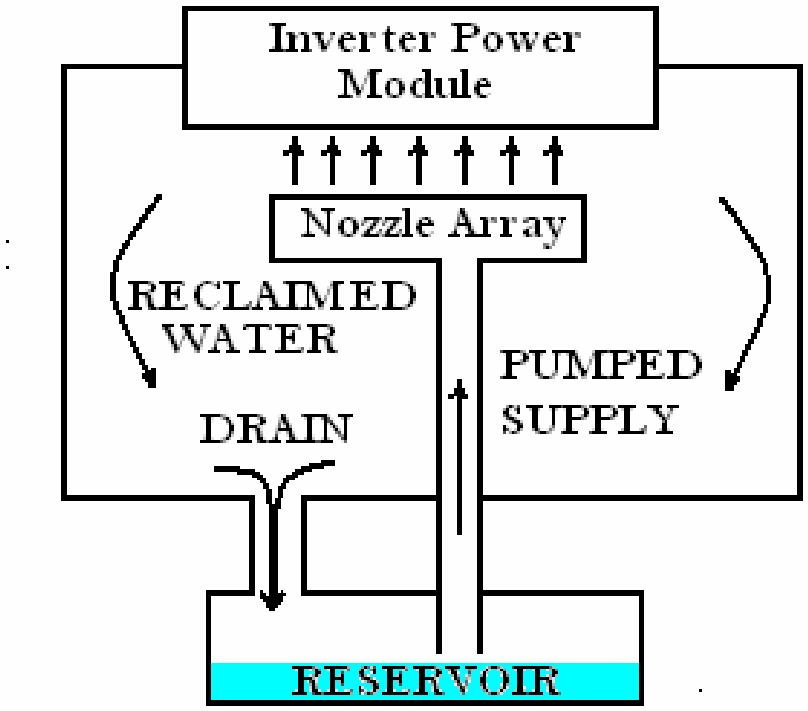


Figure 1.4. Spray cooling.

Also, the PEs are under a constant barrage of liquid from the spray providing an abundant amount of convection.

The drawback to this cooling methodology is complexity. Spray generation is non-uniform, unpredictable, and varies from nozzle to nozzle. The system also necessitates energy to provide pressure for the nozzles reducing the efficiency of the system. Nevertheless, reported heat flux capacity values have exceeded direct and indirect cooling capacities [11-12].

1.2.2.3 Thermoelectric Device Cooling

TE devices are solid state devices that do not profit from the use of cooling. Instead, TE devices draw on electrical energy along with several physical phenomena, the Seebeck, Peltier, and Thomson effects, to implement cooling. Figure 1.5 imparts a generic view of the TE device commonly found on most manufacturer websites [13-14].

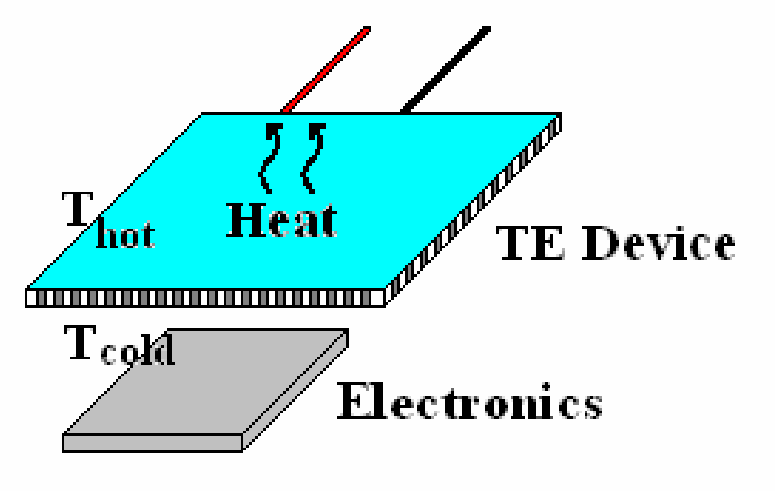


Figure 1.5. TE device.

Multiple justifications exist in exercising TE devices for cooling. TE devices are solid-state. Solid-state devices have no moving parts and as a result require no maintenance. TE devices do not depend on cooling agents. Consequently, TE devices do not necessitate refilling and containment of refrigerants. TE devices can cool below ambient temperatures. None of the aforementioned methods can cool under ambient without the application of a condenser. With a TE device, the temperature can be controlled to within fractions of a degree and can be maintained through utilizing the appropriate support circuitry. The other methods of cooling require feedback for control and must cycle between on and off in an attempt to preserve a specified temperature. TE coolers function in environments that are too severe, too sensitive, or too small for conventional refrigeration. This is a great asset particularly in HEV, FCV, or EV applications where space is limited and vibration is severe [6, 13].

Despite the large number of assets that TE devices provide, several discouraging obstacles plague TEs. The maximum coefficient of performance (COP) for these devices falls off exponentially with change of temperature as seen in Figure 1.6. Thus, operation above temperature differences of 20 ^{o}C results in extremely low efficiencies. The COP is a gauge on the performance of a system through relating the input energy to the output cooling.

TE devices also require a high thermally conductive material for heat dissipation at the interface. Without a thermally conductive material, the surface of the TE will heat/cool at a faster rate than the ambient air alone can absorb resulting in larger temperature variations across the device. These larger temperature variations not only

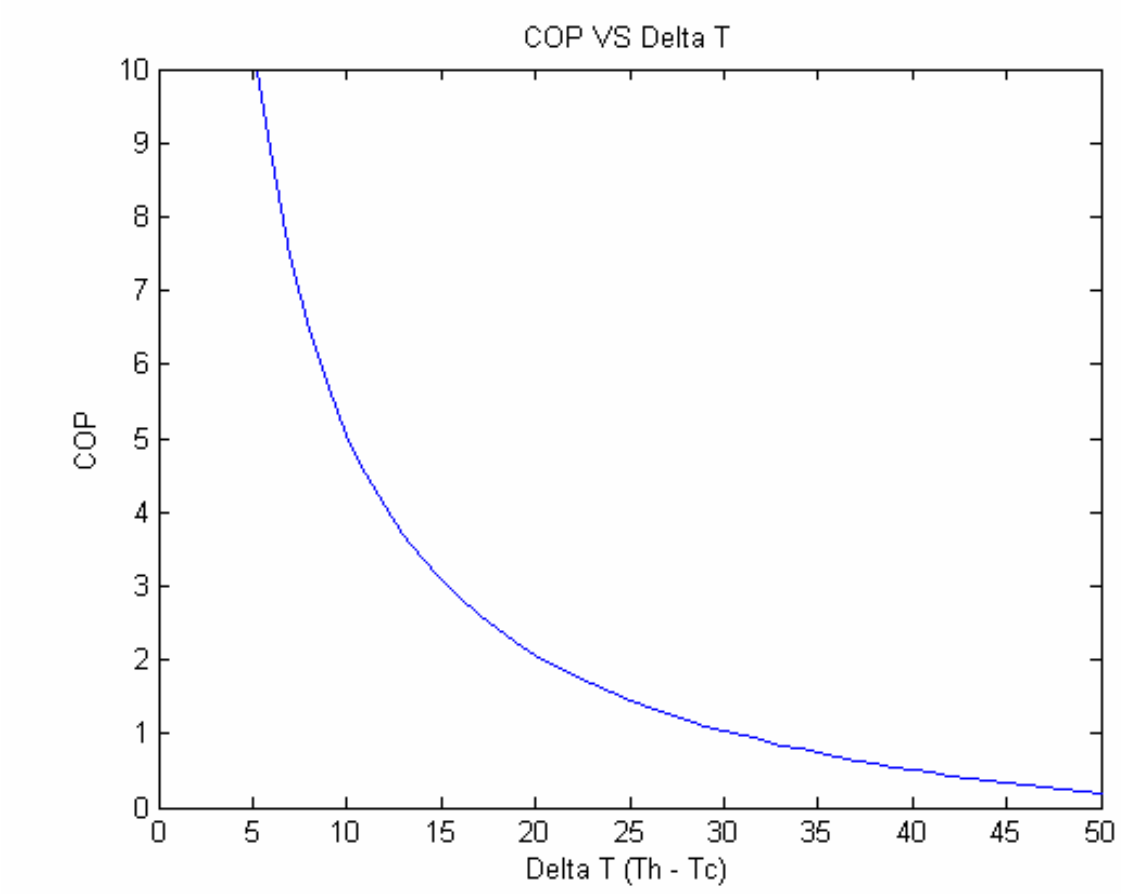


Figure 1.6. Coefficient of performance versus delta T.

induce lower efficiencies but can also bring about premature failure of the TE device [13].

1.3 Summary

To increase the efficiency and reduce emissions, the HEV, FCV, and EV vehicle types have been developed. All these vehicle types rely on PEs to function. However, the reliability and performance of PEs are directly related to the operating temperature. To prevent overheating of the PEs cooling is suggested. Multiple cooling methods have been presented. To conserve space and increase power density while working in a harsh environment, the use of TE devices in HEV, FCV, and EV applications is deemed optimum.

1.4 Outline

Since cooling has been demonstrated as a necessary component to the efficient and reliable operation of PE devices, determining the possibility of cooling PEs with TE devices will be the objective of this thesis. The following is a list of the chapters and content.

Chapter 2 embarks with the development of the TE device. A discussion of the physical phenomenon that governs these devices is conducted. This is accompanied by a review of the equations that describe the cooling capability of TE devices.

A literature survey of cooling systems that have incorporated TE devices is also performed. With each cooling system, the reasoning behind the use of TE devices is

examined. Finally, analysis on the current and future technologies of TE devices is explored.

Chapter 3 initiates a discussion of the application of TE devices in cooling PEs. A heat load and ΔT cooling requirement are computed. A model is also presented to determine the optimum operating conditions for obtaining the maximum COP.

Chapter 4 opens with a determination of the ΔT, load, and COP relationships for three and four layers of TE modules. This is followed by a comparison of the gains and losses associated with moving from three to four layers.

Chapter 5 finalizes this thesis with a description of the results of three and four layer TE modules. Application of five layers is also discussed as possible future work.

Chapter 2

THERMOELECTIC BACKGROUND

In the previous chapter, the motivation and precedence in cooling with TEs has been discussed. To better understand the functionality of a TE device, a brief overview of the physical phenomena behind TE devices, Seebeck, Peltier, and Thomson Effects, are reviewed along with the architecture of a TE.

As previously mentioned, some of the key perks in the selection of TE devices are that the device is solid state, can be operated in any environment, has very accurate control, and can cool below ambient. These advantages currently determine the relevance of TE devices. In this chapter, multiple TE applications will be also be examined along with current and future TE technologies.

2.1 Physical Phenomena of TE Devices

Three physical phenomena, the Seebeck, Peltier, and Thomson effects are the foundation behind the operation of a TE device. Of these the Peltier effect is recognized as the dominant force that permits TE devices to function. For this reason, the nickname "Peltier cooler" is often bestowed to TE devices.

2.1.1 Seebeck Effect

The Seebeck effect was first uncovered by a Estonian-Germian physicist named Thomas Johann Seebeck in 1823. Seebeck made the discovery that when applying two

different temperatures at the junctions of two dissimilar metals connected in an open circuit, a voltage potential, V_{ab}, is obtained as seen in Figure 2.1. At the subatomic level, this effect is a consequence of the thermal diffusion of electrons and holes. The thermal diffusion in a material with free electrons is greatest at the hot end. Hence, at the cold end a buildup of electrons occurs creating a charge density. This charge density creates an emf that in steady state balances the action of the thermal diffusion. Materials with low electrical and thermal conductivities have lower movement of electrons providing a higher open-circuit voltage. Since semiconductors have lower electrical and thermal conductivities than metals, semiconductors are the optimum choice in the construction of TE devices [13-15].

The relationship created by the Seebeck effect between the voltage potential and

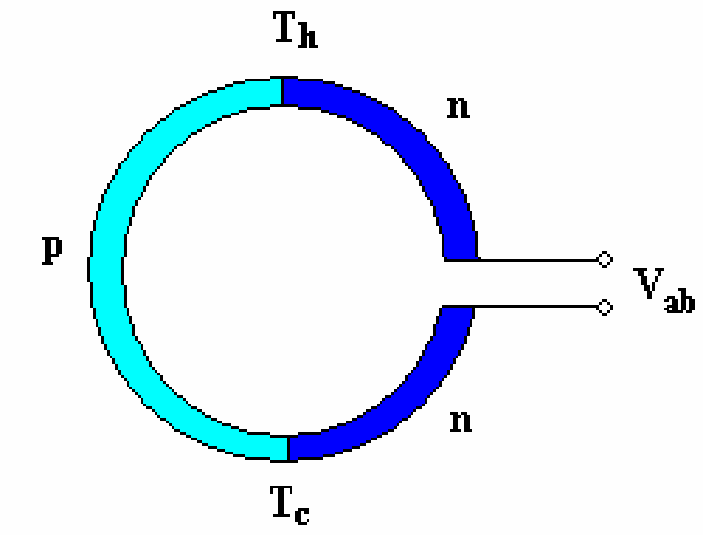


Figure 2.1. Seebeck effect.

the different temperatures at the junctions is given by the Seebeck coefficient, (2.1). This coefficient is temperature dependent and is used to help relate different materials in terms of the Seebeck effect.

$$\alpha_{ab}(T) = \frac{\Delta V_{ab}}{\Delta T} \tag{2.1}$$

2.1.2 Peltier Effect

The Peltier effect was discovered in 1834 by a French watchmaker and part time physicist Jean Charles Athanase Peltier. Peltier found that the application of a current at an interface between two dissimilar materials results in the absorption/release of heat as seen in Figure 2.2. At the subatomic level, this is a result of the different energy levels of materials, particularly n and p type materials. As electrons move from p type material to n type material, electrons jump to a higher energy state absorbing energy, in

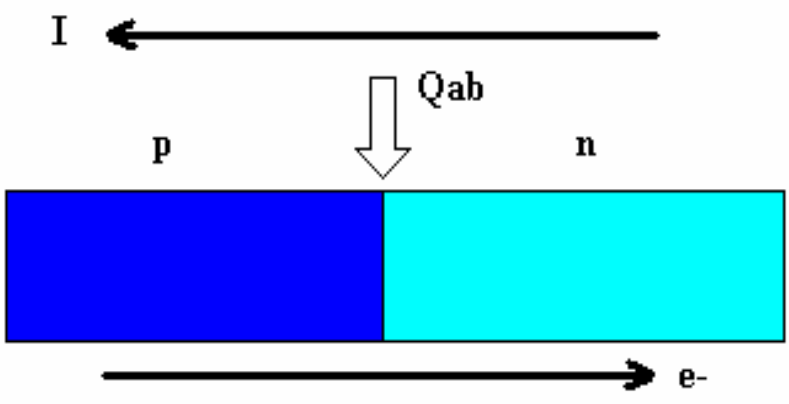


Figure 2.2. Peltier effect.

this case heat, from the surrounding area. The reverse is also true. As electrons move from n type material to p type material, electrons fall to a lower energy state releasing energy to the surrounding area.

The relationship between the amount of current and heat absorbed/released at the junction of the two dissimilar semiconductors is given by the Peltier coefficient, (2.2). The Peltier coefficient like the Seebeck coefficient is temperature dependent [13-15].

$$\pi_{ab}(T) = \frac{\Delta Q_{ab}}{I} \tag{2.2}$$

2.1.3 Thomson Effect

The Thomson effect was predicted by William Thomson in 1854. Thomson used thermodynamics to prove that the Seebeck and Peltier effects are related. Further analysis into the Seebeck and Peltier effects provided Thomson with an all together new effect, the Thomson effect. The Thomson effect is the absorption/release of a heat from a conductor with a temperature gradient as current is passed through the conductor as seen in Figure 2.3.

The relationship between the amount of current, heat absorbed/released, and the temperature gradient is given by the Thomson coefficient, (2.3) [13-15].

$$\tau_a(T) = \frac{\Delta Q_a}{I\Delta T} \tag{2.3}$$

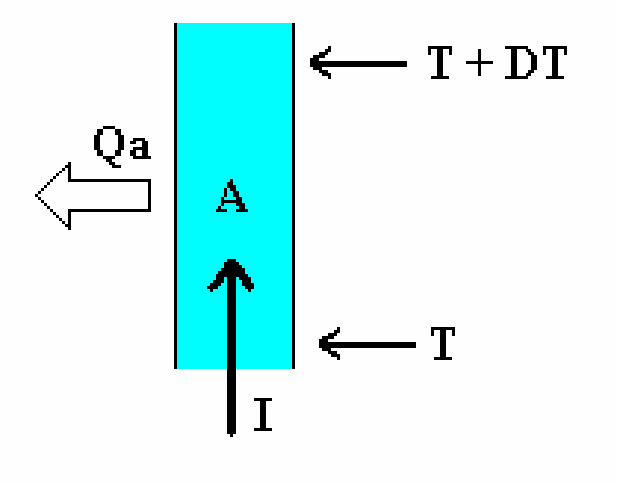


Figure 2.3. Thomson effect.

2.2 TE Architecture

All TE devices have a similar construction. A sequence of p type and n type materials, usually Bismuth Telluride, are linked in series by conductors as in Figure 2.4. The exterior of the TE device is usually coated with a ceramic that provides both thermal conductivity and electrical insulation. The manufacturer can provide contrasting TE devices by altering the associated interconnection surface area, length (leg length), doping levels, and quantity of the p and n type junctions.

To perform cooling with a TE device electrical energy is required. Application of a voltage results in the flow of current through the p and n type materials. Finally, through the Peltier effect, one side of the TE device absorbs heat and the other releases the heat. The side that that absorbs the heat is usually denoted as the cold side (T_c), while

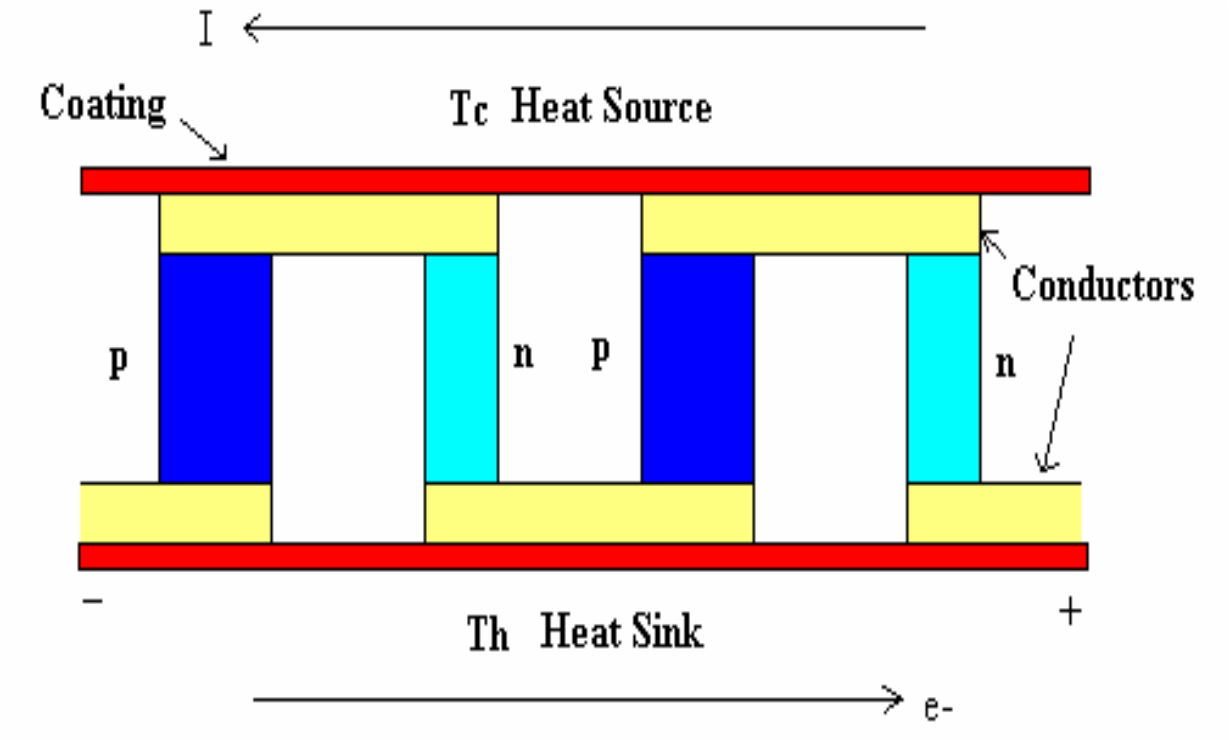


Figure 2.4. TE device layout.

the side that releases the heat is designated as the hot side (T_h).

2.3 TE Properties and Equations

The equation that governs the amount of possible cooling in watts (Q_c) of a TE is a function of the Peltier effect, thermal losses, and conduction losses, (2.4), where N is the number of interconnections, K is a constant associated with the thermal conductivity,

$$Q_c = N\left((\alpha_p - \alpha_n) I T_c \; - \; K(T_h - T_c) \; - \; \frac{I^2 R}{2} \right) \qquad (2.4)$$

Peltier Effect *Thermal* *Conduction*

R is the resistance, I is the input current, and α. is the Seebeck coefficient. Note that the n and p designations, relate to the material, n and p type. The variable K is a function of the thermal conductivity (λ) of the material, area (A), and length of the channels (L), (2.5). R is a function of the electrical resistivity (ρ) of the material, area, and length of the interconnections, (2.6). This equation is often used as the sole reference equation in determining the amount of cooling the device can accomplish.

$$K = \frac{\lambda_p A_p}{L_p} + \frac{\lambda_n A_n}{L_n} \qquad (2.5)$$

$$R = \frac{\rho_p L_p}{A_p} + \frac{\rho_n L_n}{A_n} \qquad (2.6)$$

The amount of heat dissipated (Q_h) on the hot side of the TE device has a similar equation to that of the cold side. However instead of the electrical power reducing value of Q_h, the electrical power is summed with the quantity of heat requiring removal as seen in Figure 2.5, (2.7). The electrical energy input to the system is lost in the form of heat and must be sent out of the thermoelectric device, (2.8).

$$Q_h = N\left((\alpha_p - \alpha_n) I T_h - K(T_h - T_c) + \frac{I^2 R}{2} \right) \tag{2.7}$$

$$Pin = V * I = N\left((\alpha_p - \alpha_n)\Delta T + IR\right) * I \tag{2.8}$$

To determine the best semiconductor material to use in the fabrication of a TE device, the Figure of Merit, Z, is applied, (2.9). The Figure of Merit uses the Seebeck

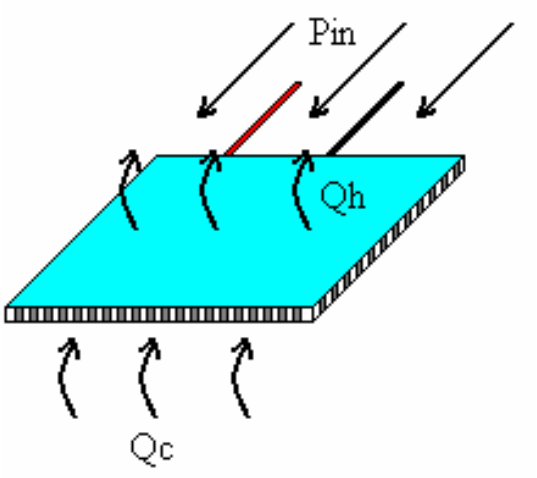


Figure 2.5. Heat flow.

coefficient, thermal conductivity, and electrical resistivity, since these device dependent parameters play the largest role in the calculation of Q_c. The use of Bismuth Telluride comes from the fact that this material has one of the highest figures of merit [13-15].

$$Z = \frac{(\alpha_p - \alpha_n)^2}{\left((\lambda_p \rho_p)^{1/2} + (\lambda_n \rho_n)^{1/2}\right)^2} \tag{2.9}$$

2.4 Past Experiments Involving TE Devices

In this section, multiple cooling applications using TE devices will be reviewed. These applications include cooling laser diodes, refrigeration systems, and hermetic cooling systems for cooling electronics.

2.4.1 Laser Diodes

Today, laser technology can be located in almost every field. Lasers are used in the medical profession to perform surgery, in the manufacturing sector as cutting instruments, in landscaping to determine distance, and in communications to transfer information [16].

In particular, laser technology is essential in communications due to the achievability of a high bit transfer rate (>2Gb/s). Another asset to laser communications is the multiple mediums of information transfer. Lasers can be transmitted by direct line of sight or by means of a fiber optics cable. Furthermore, multiple signals along a single pathway can be achieved with high quality and low losses [17].

Nevertheless, several limitations with laser implementation exist. Laser lifetime and operational efficiency suffer severely with increasing temperature. Additionally, the necessity for the devices to be extremely small prevents conventional cooling from being useful. Temperature does not only influence the efficiency of the laser diode, but the wavelength of the laser as well. Pronounced temperature changes in the diode can cause distortion in the wavelength.

In 1967, IBM began to investigate the application of TE modules to cool an optical diode employed in a computer communication data link. The relevance in cooling with TE devices came from the size, environment, and cooling control requirements demanded by the optical diode.

The TE cooling system IBM incorporated in their computer is seen in Figure 2.6. Here, a two-stage cascaded TE device was utilized with the hot side temperature maintained at 55 ^{o}C and the cold side at -25 ^{o}C. As noted in Chapter 1, a secondary source of heat removal is crucial for the TE to operate. In this case, an indirect cooling method, or water-cooled loop, was implemented to remove the heat from the TE and radiate it to the ambient air. A vacuum pump was also consolidated to counteract any moisture buildup on the surface of the TE devices. This particular system had the potential of removing 3 watts of heat [18].

Another more modern cooling alternative for laser diodes can be seen in Figure 2.7. Similar packaging constraints as that of the IBM computer hindered the direct application of conventional cooling. Instead, the TE devices draw the heat from the laser

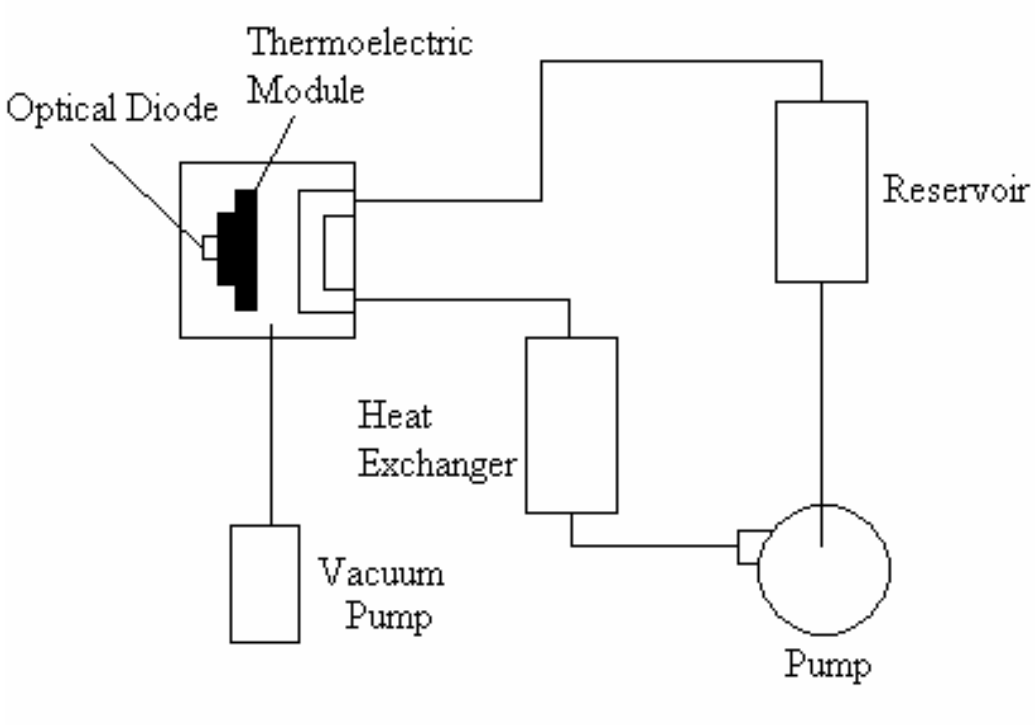


Figure 2.6. Optical diode cooler.

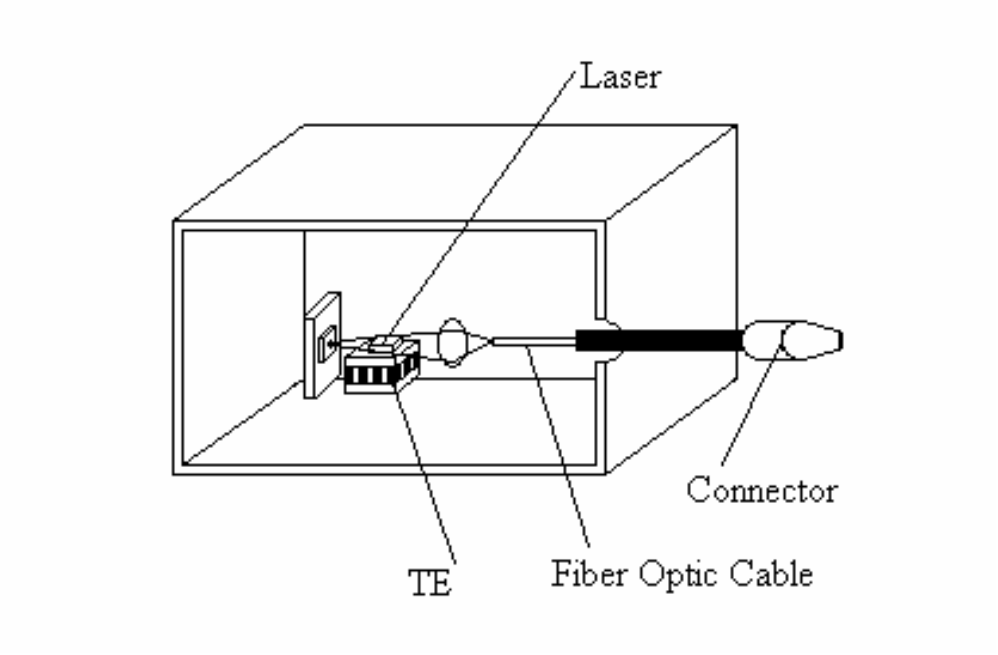


Figure 2.7. Laser diode cooler.

diode and expedite it through a heat sink to air. This system had the means to displace approximately 1W of heat.

2.4.2 Automotive Cabin/Seat Air Conditioning and Heating

Since the invention of air conditioning by Willis Haviland Carrier in 1904, countless applications for the air conditioner have been developed [19]. Air conditioningand refrigeration systems have progressed from being a simple convenience to a necessity. This is undeniably true in the automotive industry. Early automobiles lacked air conditioning, since refrigeration technology in this period was still under development. Even when air conditioners began to be incorporated into the automobile, air conditioning was still considered an option and not a requirement. Now, all automobiles contain air conditioning systems as customers deem these systems as a necessary luxury. Unfortunately, most automotive air conditioners consume a large amount of space and use refrigerants that are harmful to the environment. Therefore in an attempt to be more environmentally friendly, GM has begun to affix TE devices into the automobile to cool occupants.

To cool vehicle passengers, TE devices are directly imbedded into the seat as seen in Figure 2.8. By incorporating the TE device within the seat, the TE device can almost straightaway cool/heat the occupant. This permits the device to operate at a low heat transfer rate and at low ΔTs for maximum performance, providing passenger comforts without a taxing cooling system. Since these devices are inherently reliable, no maintenance is necessary unlike current automotive air conditioning systems. Furthermore, these devices are compact and quiet [20].

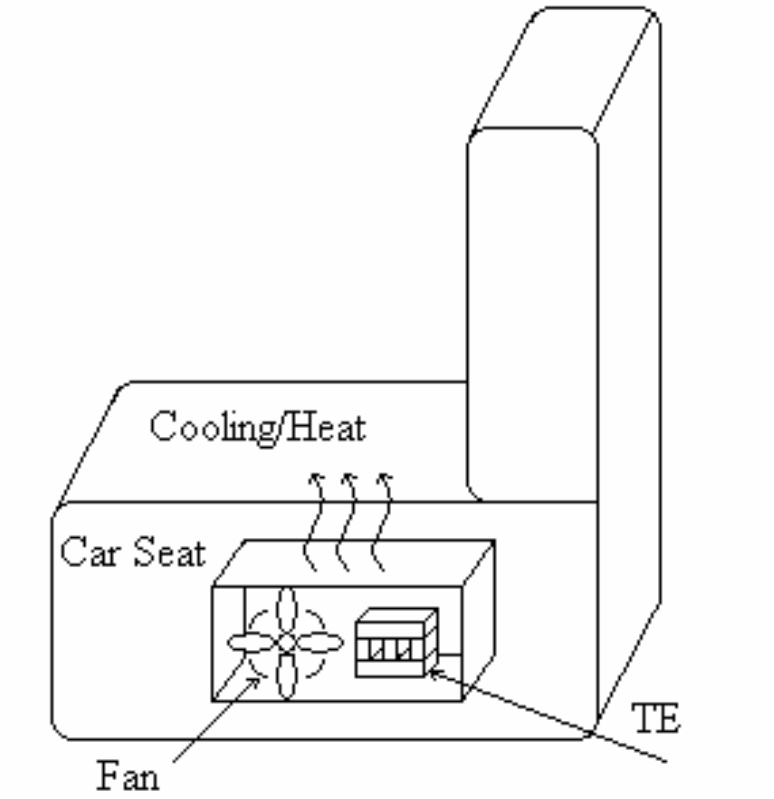


Figure 2.8. Car seat cooler.

2.4.3 Automotive Cooler

The previous TE device application reviewed was solely focused on cooling the occupants of a vehicle. The TE device application shown in Figure 2.9 can be used in multiple vehicle applications. This system could be used to cool the gases from the compression stage of an engine turbocharger as a means to increase horsepower. This could generate an increase in efficiency of the vehicle. Another possible application for this system is cooling of the engine and/or transmission fluid. This would essentially remove the demand for a large radiator. Last, the occupants in the vehicle could also be cooled with this type of system through the use of fans.

In operation of this cooling system, a hot fluid or gas, depending on the application, is passed through a chamber. Large plates are attached to this chamber to

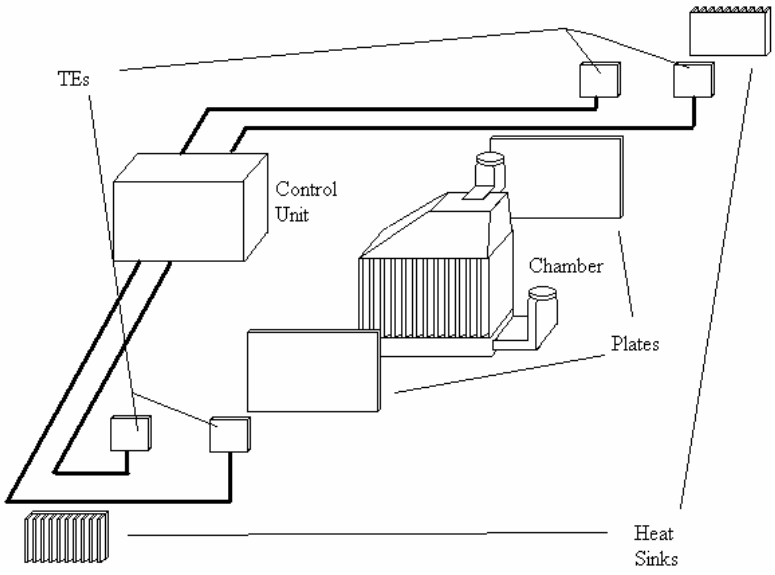


Figure 2.9. Automotive thermocooler.

provide a highly thermally conductive median for the TEs to extract the heat. Large heat sinks connected to the opposite side of the TE devices supply the outlet for the heat to be transferred to air. A control unit administers the correct amount of power to the TE device for appropriate cooling. Here, through the use of an assorted collection of cooling methods, TE devices can be used to cool large sums of heat [20].

2.4.4 Hermetic Cooling of Power Electronics

In some applications, the necessity exists to isolate electronics completely from the environment. The environment could be contaminated with a large accumulation of particles that could cause harm to the electronics. Likewise, the electronics could be required to operate in marine conditions, where water completely engulfs the container.

In either case, normal conventional cooling cannot be used under these conditions. Figure 2.10 shows an example of a hermetic conventional and TE cooling system.

In the hermetic conventional cooling system, a heat sink is utilized to extract the heat from the electronics and deliver it to the ambient air in the container. A large fan is appropriated to exhaust the waste heat from the container. With harsh environmental conditions present, a large filter is often necessary at the input to remove incoming particles. This filter is not only spacious but also heeds the flow of air to the electronics. Discouragingly, to increase the air flow for maximum cooling, the size of the filter must be further increased resulting in an added reduction in available space. Unfortunately, this type of cooling system is not applicable for marine conditions. Similar to the hermetic conventional cooling system, the TE cooling system incorporates

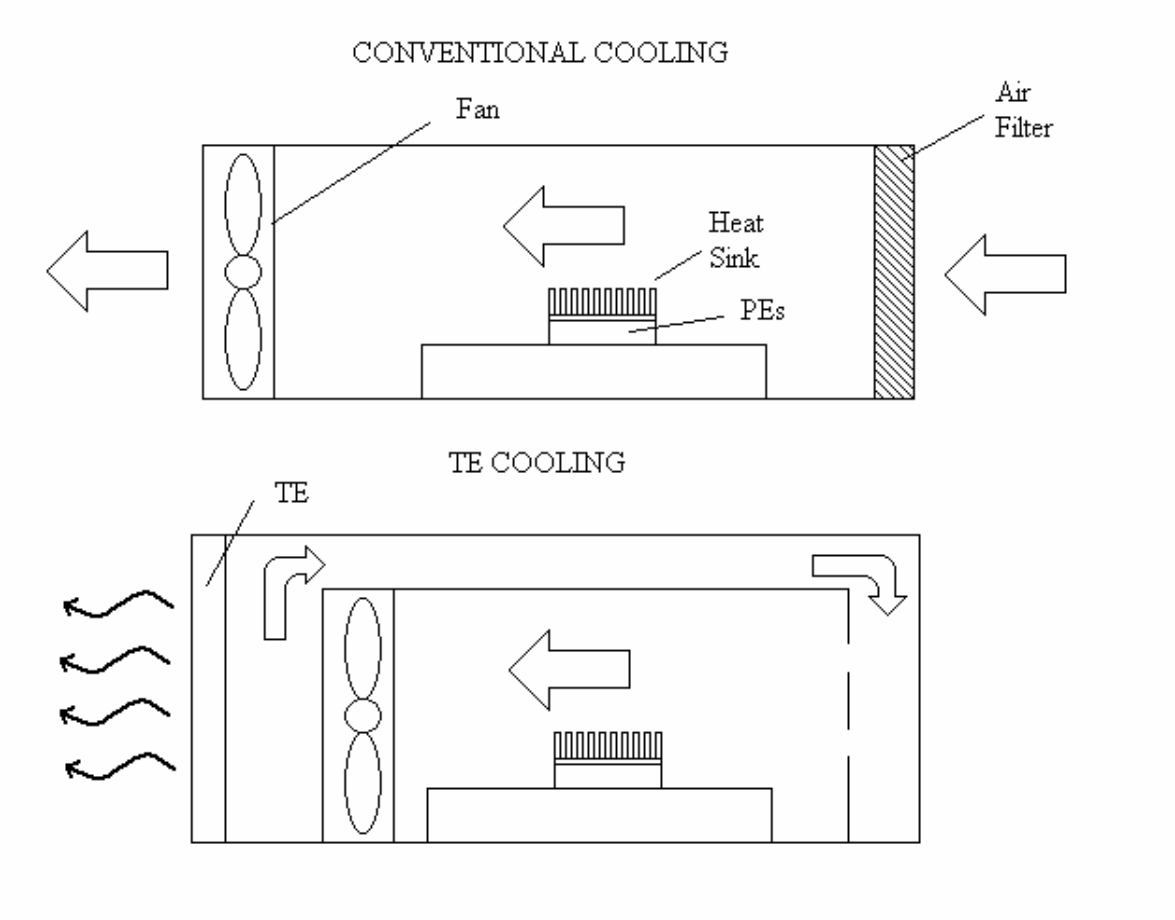


Figure 2.10. Hermetic thermocooler.

a heat sink to remove the heat from the power electronics. However, the similarities stop there. Instead drawing in and then exhuming air from the container, air is circulated within the container through the application of a fan. TE devices mounted on the interior of the container extract the heat from the air and purge it from the container. This not only accommodates the electronics with complete isolation from the environment but also indulges a much more compact construction [21].

2.5 Advanced TE Technology

As evident from the aforementioned applications, current TE technology has much to be desired. Most of the TE devices commonly found in the market have low heat fluxes comparable to that of conventional cooling. Table 2.1 shows a list of several companies that produce TE devices along with some model parameters. Notice that all these devices, save one, have a maximum cooling capability of 10.75W/cm^2. Micropelt has managed to obtain as much as 60W/cm^2 on their TE models. This is due to the employment of a different technology.

An abundant quantity of avenues has been researched to increase the performance of TE devices. Most of these routes have been associated with finding a more suitable material but have not met with success. The newest propositions in boosting the performance of TE devices has involved sizing of the material.

Most TE devices on the market have heights in the millimeter range. New micro-technologies have permitted the construction of TE devices that are as much as 10 to 100

Table 2.1 Manufacturer Data

Manufacturer	Qmax W/cm^2	Delta Tmax C	$Price/cm^2$	$Price/(W/cm^2)$
Advanced Thermoelectrics	5.00	72.00	$1.24	$5.60
INB Products	10.75	69.00	$1.75	$2.60
Marlow	4.44	66.00	UA	UA
Melcor - (high temperature series)	4.09	63.00	$1.32	$5.68
Micropelt (Thin Film)	60.00	31.90	$3,495.84	$0.62
TE Technologies (high temperature series)	10.75	67.00	$1.98	$2.95
Tellurex	4.09	79.00	$1.22	$5.26

times smaller, but have equal cooling capability. As seen in Figure 2.11, the two main technologies that have prevailed with this concept are thinning of bulk materials and the adoption of thin film technology.

Thinning of bulk materials works with equivalent materials but accomplishes the enhanced performance through a cutback in size. From this technology, TE devices with 200 μm thicknesses and anticipated cooling capabilities of 80W/cm2 have emerged. This type of design, nevertheless, has several associated conundrums. The largest dilemma is the solder connections. The solder junctions add significant resistance that accrues dramatic reductions of the maximum ΔT and cooling capacity of the TE device.

Thin film technology implements a unique fabrication method to condense the size of the TE device. Instead of eliciting multiple components in the construction of a single TE device, a single element can now be manufactured. The sizable gain in size and performance of the TE transpires with the loss of the solder connections. As mentioned previously, the solder is the key fault to the addition of resistance and size and reduction in the maximum ΔT. With this design, the thickness can be as small as 20 μm and yet have a cooling capability of 700W/cm^2.

Micropelt has developed the thin film TE device seen in Figure 2.12 with a cooling capacity of 0.313W at 85^{o}C. Although this appears to a meager coolingmagnitude, this device is extremely small with a total area of 0.52mm^2 and a subsequent maximum heat flux rate of 60W/cm^2. Nonetheless, greater cooling capabilities are expected in the future with thin film technology [23-24].

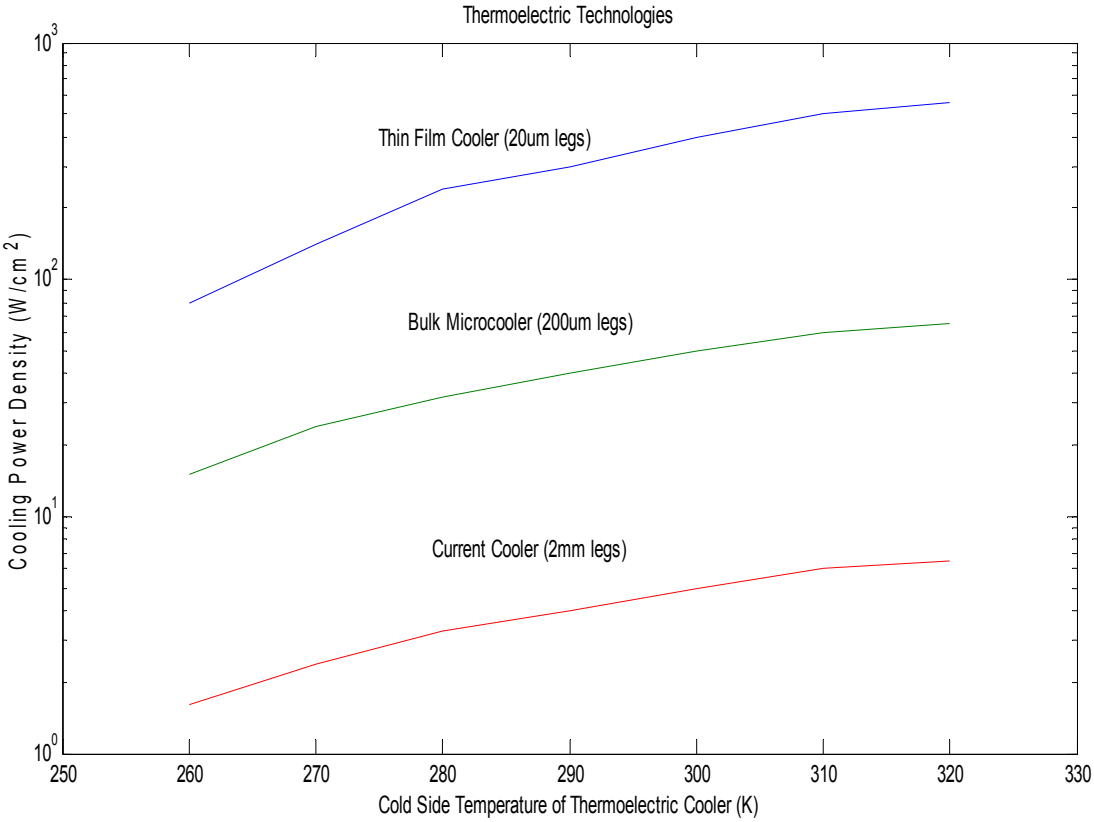


Figure 2.11 Thickness influence.

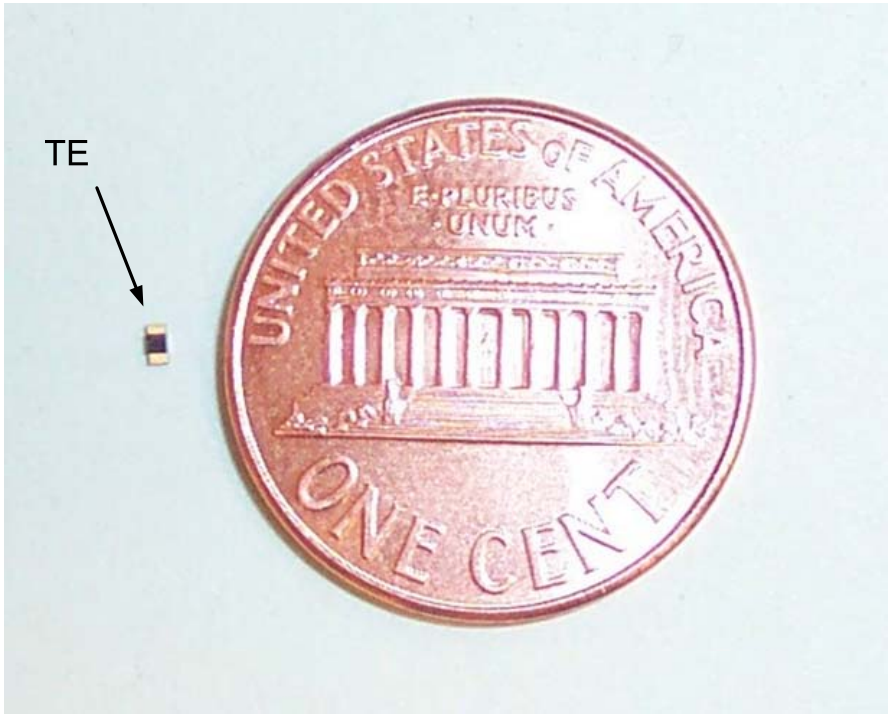


Figure 2.12 Micropelt TE cooler.

2.6 Chapter Summary

In this chapter, an exploration into the physical phenomenon behind the operation of a TE device was performed. This aided in the development of the construction of TE devices along with several equations relating the cooling capability of a TE device.

Various cooling schemes incorporating TE devices were also studied. TE devices were found to be applied in the cooling of laser diodes on account of the size, environment, and control requirements, in refrigeration systems due to environmental benefits and diversification of application, and in marine locations owing to the harsh environment. As examined in the last section, one compelling factor that prohibits further implementation of TE devices is the current cooling capability of TE devices. Although, current prospects on TE device technology are low, the promise of thin film technology is great. Additional development of thin film technology will motivate the utilization of TE devices into many more applications.

In the next chapter, cooling PEs with TE devices will be scrutinized. A heat load will be ascertained through several calculations along with a ΔT that the TEs must overcome for adequate cooling. The computational techniques applied will be defined.

Chapter 3

LOAD DETERMINATION

In the last chapter, the physical phenomena that allows TE devices the capability to function was examined. This motivated the investigation into the equations that govern the cooling capability of TE devices. With this background knowledge, a literature survey of experiments conducted with TE devices and a query into current and future TE technology was conducted.

In this chapter, the application of TEs in cooling PEs will be investigated. The necessary ΔT and heat load demand will be established.

3.1 Cooling PEs

From Chapter 2, the possibility of cooling PEs in hybrid vehicle applications with current TE technology appears to be remote. A 50kW insulated gate bipolar transistor (IGBT) driven inverter, operating at a continuous operation of 30kW and an efficiency of 97% will still have an average loss of 900W or about 150W per IGBT. Considering the size of a single IGBT die can be about $1cm^2$, this evaluates to a $150W/cm^2$ cooling requirement. This is the best case scenario. Most likely the efficiency of the inverter will be lower, resulting in more heat and a further increase in cooling requirement.

As noted in the previous chapter, the current maximum cooling capability of a TE device is about $60W/cm^2$. Obviously this will not meet the needs of the cooling requirement of the IGBTs in an inverter.

3.2 DC-Link Capacitor

During the operation of an inverter, ripple current is induced by the switching of the IGBTs. To protect both the dc supply and stabilize the DC link, a typical inverter employs a DC link capacitor to absorb the ripple current as seen in Figure 3.1. However, absorbing this ripple current comes at a cost. The ripple current generates heat in the capacitor that is a function of the equivalent series resistance (ESR) and ripple current, (3.1). To prevent an increase in temperature this heat must be removed [25].

$$P = Irms^2 ESR \tag{3.1}$$

Ripple current dictates not only the amount of heat that is lost in the capacitor, but also adds a restraint on the operational temperature. As evident from Figure 3.2, the

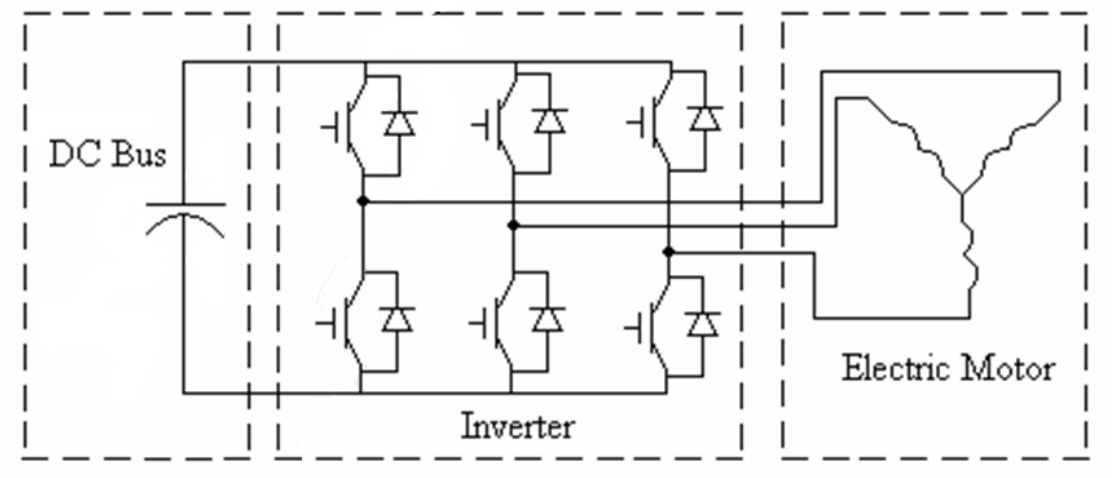


Figure 3.1. Inverter model.

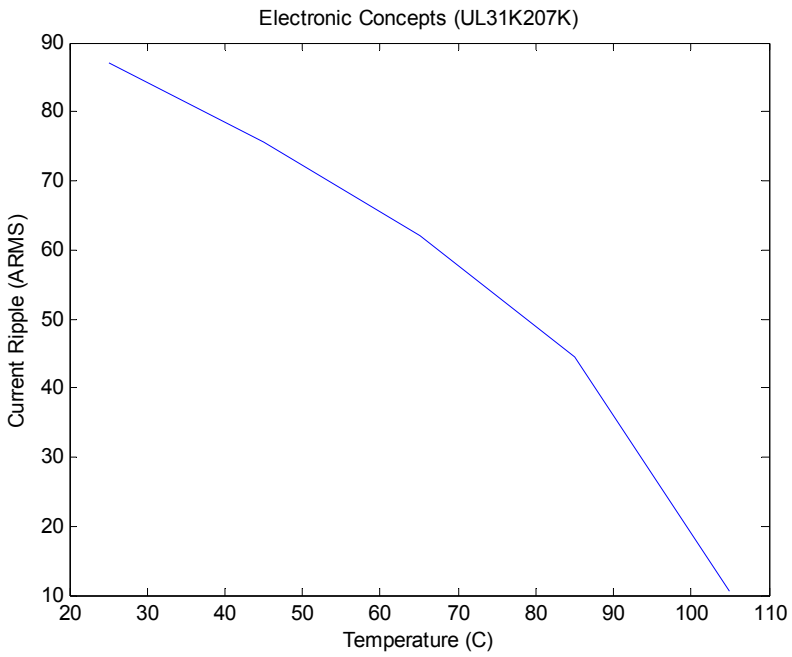


Figure 3.2. Capacitor ripple current vesus temperature rating.

ability of a capacitor to manage ripple current declines significantly with increasing temperature. Therefore, the survivability of the capacitor is fully dependent on selecting a capacitor that meets the ripple current demand at a given temperature and maintaining operation below this temperature.

3.3 Load Determination

In the evaluation of the heat load necessary for TE cooling, the Toyota Prius configuration is considered. The Prius uses a 50kW inverter attached to a 500Vdc bus supplying a RMS current of 220 A will be scrutinized.

In the following sections, calculations of the maximum ripple current will be carried out. This will provide an indication of the amount of heat necessary for the TEs to remove and the operating temperature of the capacitor.

3.3.1 Capacitor Ripple Current

To obtain the maximum amount of heat dissipated across the capacitor, a value for the maximum current ripple must be enumerated. Assuming that the inverter is using PWM switching, Hava, Kerkman, and Lipo have developed an equation relating a constant known as the current ripple factor, (3.2), to the modulation index (M) and power factor angle (θ) [26].

$$K = \frac{2\sqrt{3}}{\pi^2} M + \left(\frac{8\sqrt{3}}{\pi^2} - \frac{18}{\pi^2} M \right) M \cos^2 \theta \tag{3.2}$$

To determine the most severe load, the power factor is assumed to be 1, and the the inverter is driven with in full over modulation, or M = 4/π. This leads to a value of 0.722 for the current ripple factor. An equation connecting the ripple current to the ripple current factor and the load current also has been established, (3.3). With a load current of 220Arms, a ripple current of approximately 187Arms is produced.

$$I_{INRMS} = \sqrt{K * I_{LRMS}{}^2} \tag{3.3}$$

3.3.2 Capacitor Temperature

From the previous section, a capacitor, or multiple capacitors, with the potential of sustaining a 187A ripple current must be located. Electronic Concepts film capacitor model number UL31Q157K has the ability to bear 80Arms ripple at 70^{o}C. To provide adequate ripple current protection, and to sustain acceptable lifetime three of these capacitors are to be used in parallel and the temperature is to be limited to 70^{o}C.

Nevertheless, the capacitors are often placed in environments with temperatures exceeding the 120^{o}C range. This ensures that a minimum ΔT of 50 ^{o}C is required.

3.3.3 Heat Load

With the magnitude of the maximum ripple current and access to the capacitor data sheet, the heat load can be computed. The value of the ESR at 10kHz for this capacitor is 3.8mΩ. This accrues a power dissipation of approximately 45W. Yet, this amount of heat is over a large area, therefore it is acceptable for a TE application.

3.4 Layering TE devices

Often the demand of a cooling application requires a larger ΔT than is possible for one single device. Hence, multiple TE devices can be used to increase the overall possible ΔT as seen in Figure 3.3. However, the addition of TE devices comes at a cost.

As previously mentioned the heat departing the hot side of a TE device does not equal the energy entering a TE device. This is a consequence of the electrical energy input to the TE device. The electrical energy along with accommodating the Peltier effect

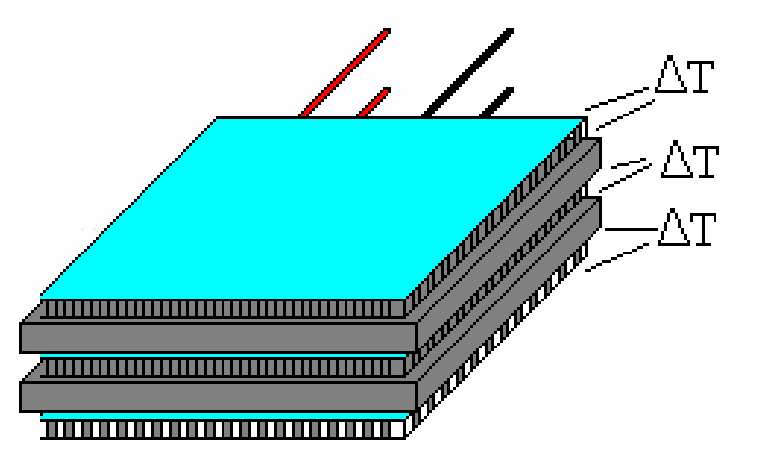


Figure 3.3. Layering TE devices.

contributes to the heat. This can be extremely problematic when multiple TE devices are in series. Each TE device in series subsidizes more heat that must be evacuated in the next TE device. Ultimately, the final TE device must dissipate the gross electrical energy of the TE network and the original heat load. Depending on the TE configuration, this can either cause the COP of the TE cooling system to increase significantly or plummet.

In the previous section, the expectant overall ΔT was estimated to be greater than 50^{o}C. For modeling purposes, Micropelts TE device model number MPC-D901-M44 has been chosen, due to the advanced technology and high cooling capacity that this device can perform. The device has the performance curves shown in Figure 3.4 at 25^{o}C. At 25 ^{o}C the maximum ΔT is 21.9 ^{o}C, however, this increases to approximately 30 ^{o}C at about 125 ^{o}C hot side temperature. In either case, a single TE device will not meet the cooling needs of the capacitor.

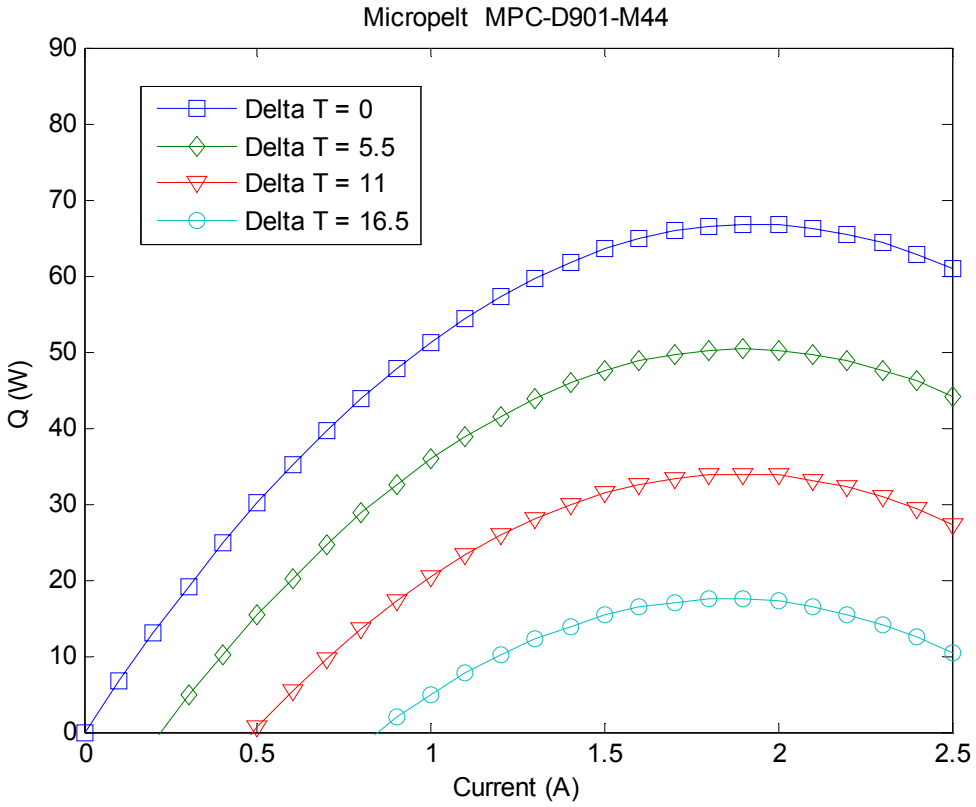


Figure 3.4. TE performance curves.

3.5 Model Development

To develop a working model of a TE device such as Micropelts MPC-D901-M44, several difficulties must be overcome. First, the Seebeck coefficient, thermal conductivity, and resistance of Bismuth Telluride vary signifcantly with temperature. This must be incorporated into the model for accuracy. Second, the amount of possible variations in layering TE devices is quite large. Each layer can have a different ΔT, consuming a distinct amount of power that must be removed by the next layer. This adds many dimensions of complexity.

3.5.1 Bismuth Telluride and Temperature

The optimum method for application of the effects of temperature on the Seebeck coefficient, thermal conductivity, and resistivity of Bismuth Telluride is to develop equations relating temperature to these values. To do so, data comparing temperature to these properties must first be uncovered.

The data seen in Figures 3.5, 3.6, and 3.7 was located from several sources. The commands in Matlab, polyfit and polyval were employed to create equations that related these properties to temperature.

To provide accuracy, the TE device analysis is subdivided into seven sections each with a separate average temperature as seen in Figure 3.8. This is especially important when a large ΔT exists over the device. For each section, a value of the Seebeck coefficient, resistivity, and thermal conductivity is calculated in terms of the average temperature of that portion. Finally, these values are averaged and applied to the cooling equation.

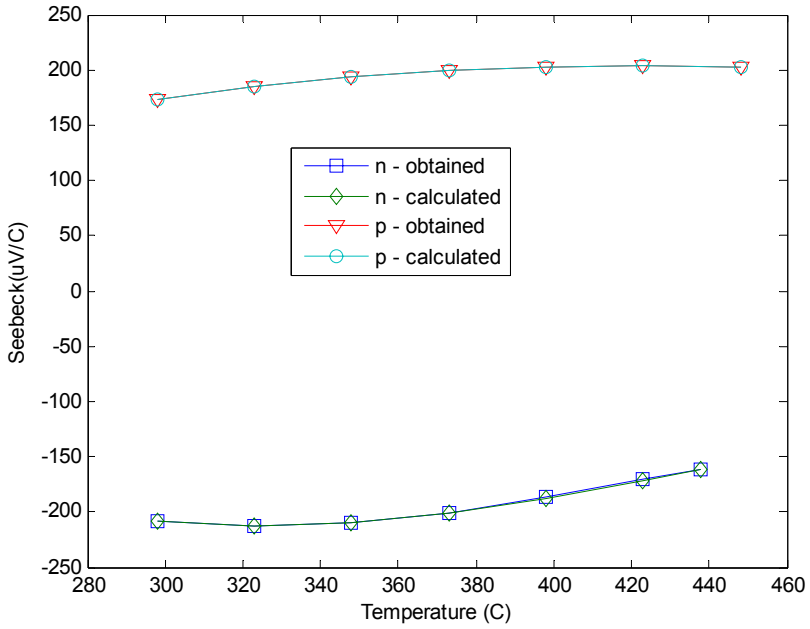


Figure 3.5. Seebeck versus temperature.

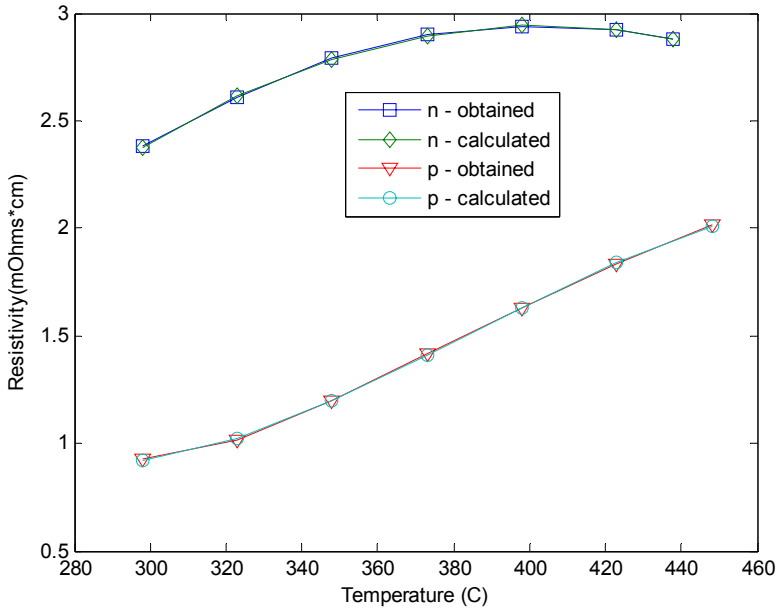


Figure 3.6. Resistivity versus temperature.

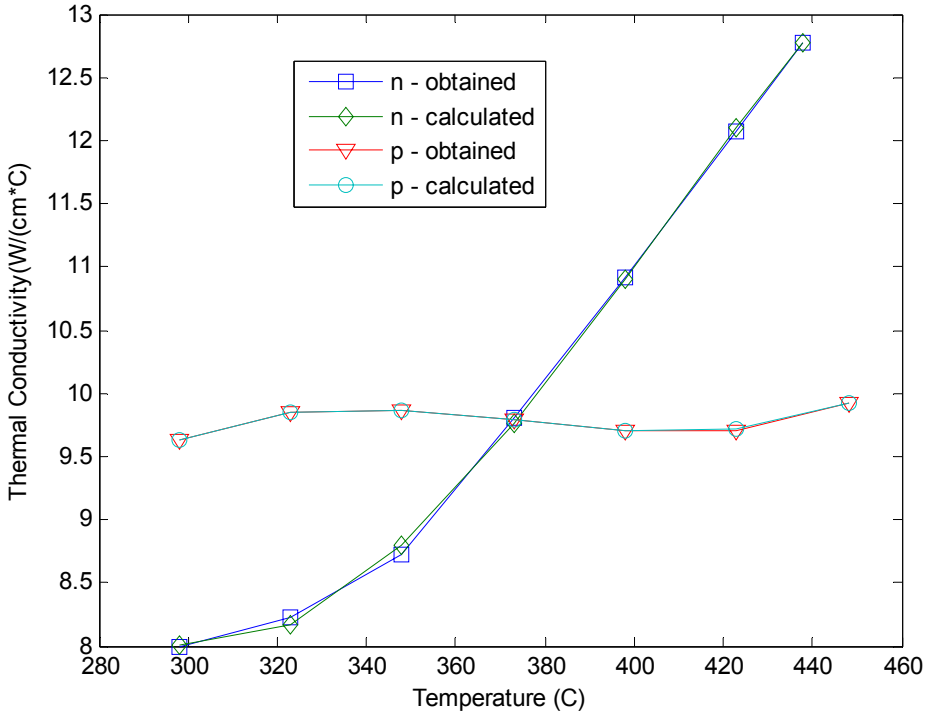


Figure 3.7. Thermal conductivity versus temperature.

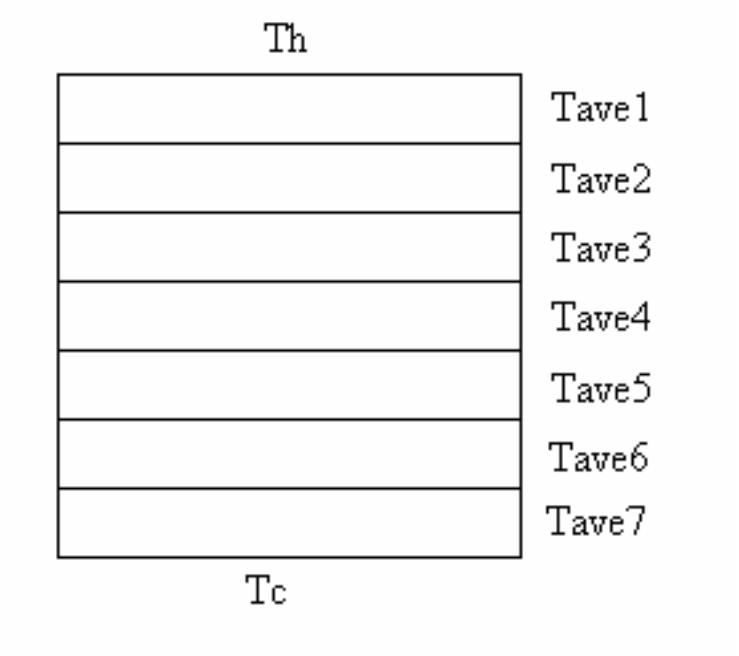


Figure 3.8. TE sections.

3.5.2 Model

The model applied to represent the cooling capacity, is associated with the equations (2.6) and (2.8). A matrix of the possible ΔT values for each layer is constructed assuming an overall maximum ΔT. Each ΔT combination is applied to the cooling equation with a range of currents to create an array of cooling quantities in respect to a particular overall ΔT.

To use this array in the development of multiple layers, a specific coolingquantity is chosen. This cooling quantity is found in the cooling array with respect to a particular current as seen in Figure 3.9. The corresponding current is then applied to the voltage waveform to determine the required voltage as seen in Figure 3.10. Together the current and voltage are used to determine a necessary input power. This input power is added to the next layers cooling quantity and the process is repeated. With the input power, the COP can be enumerated.

The COP is given in terms of the input power and heat removed and provides insight into the efficiency of the system (3.4). Good values for COP in device cooling are between 2 and 3 [27].

$$COP = \frac{Q}{Pin} \tag{3.4}$$

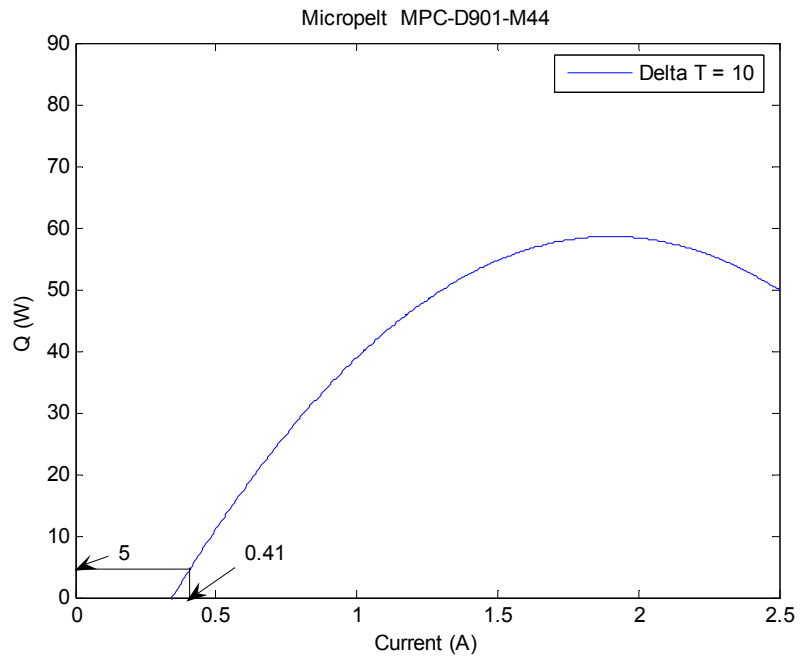


Figure 3.9. Cooling versus current.

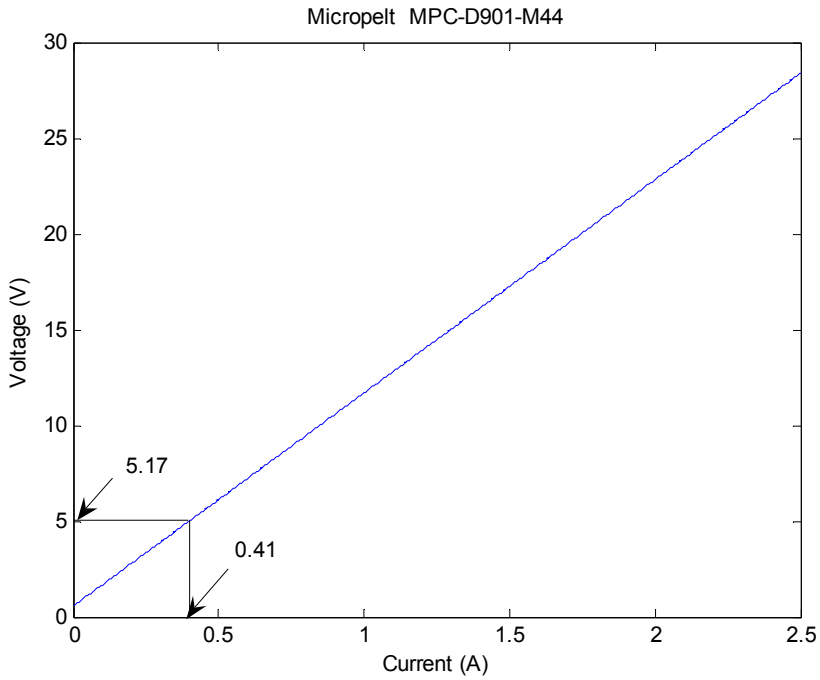


Figure 3.10. Voltage versus current.

3.5 Summary

In this chapter, cooling IGBTs was considered unmanageable with current TE technology. However, an inverter capacitor was also found to require cooling. Hence, heat dissipation and maximum ΔT calculations were produced to help instigate cooling of the capacitor with TE devices. Since, the maximum ΔT required exceeded the ΔT of a single device, layering TE devices was proposed.

Issues involving modeling were also examined. The effects of temperature on the properties of Bismuth Telluride were incorporated into the model. A methodology to unmask the necessary input power per device and ascertain the overall COP was also revealed.

In the next chapter, the combinations of ΔT that present the largest COP values will be shown for 3 and 4 layers of TE modules. Comparisons of the cooling capacity along with a range of ΔTs will also be made. Based on the cooling quantity determined in this chapter, calculations will made for sizing of the TE array.

Chapter 4

RESULTS

In the last chapter, calculations of the cooling requirements yielded a 45W load at a ΔT greater than $50^{o}C$. This large value of ΔT established that layering TE modules is necessary.

In this chapter, three and four layers of TE modules are considered. COP, ΔT, load, and area relationships substantiated by calculation are examined. The data collected in this chapter should supply insight into the optimum choice of the number of TEs and operating condition of each TE.

4.1. Three Layers

For this design, a minimum of three layers is essential to meeting the minimum requirements of a ΔT of $50^{o}C$. Although the maximum ΔT of the TE device under question is $30\ ^{o}C$ which seemingly concedes two layers, the maximum amount of cooling at this ΔT is 0. Hence, at least three layers of TE devices must be utilized.

In the following sections, the COP, ΔT, load, and area relationships will be investigated for three layers.

4.1.1. Maximum Cooling Capacity Versus Delta T

During data collection, a maximum overall loading was uncovered for each ΔT. This maximum loading limit in terms of ΔT resembles a linear line as seen in Figure 4.1.

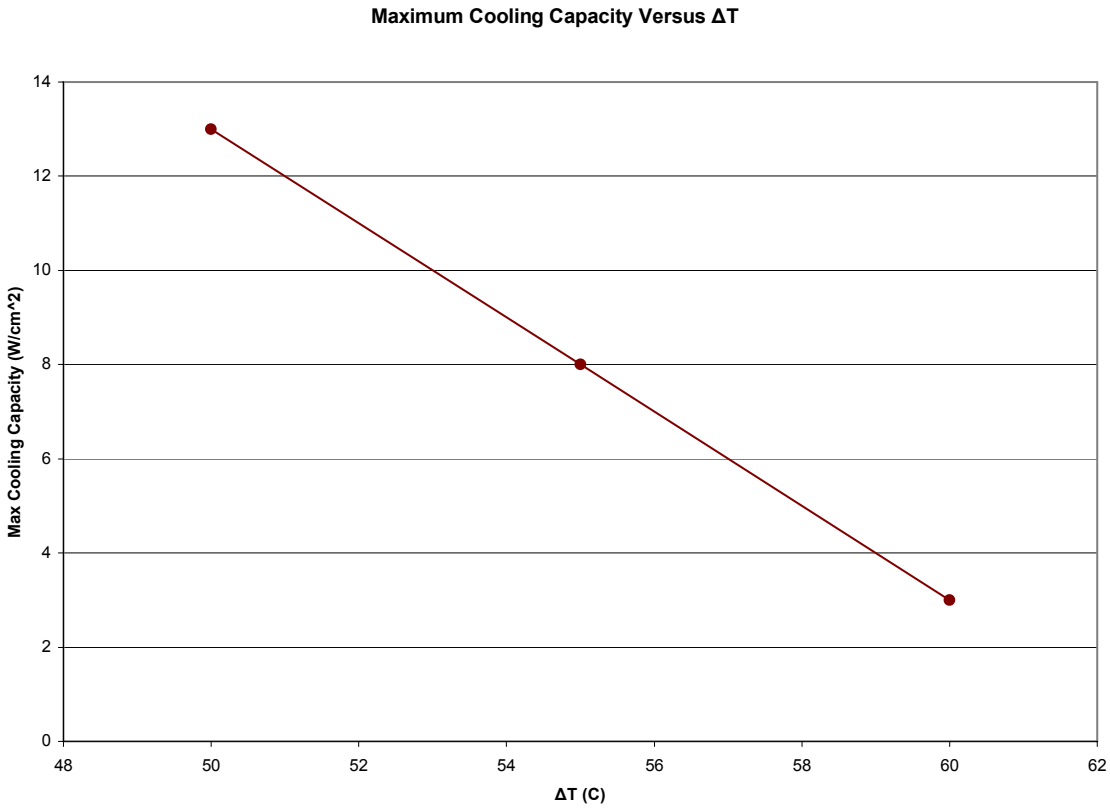


Figure 4.1. Max cooling capacity versus ΔT for three layers.

The slope of this linear relationship is approximately 1W/(cm^2 ^oC). Hence, for every 1 ^oC drop in the ΔT an increase of 1W/cm^2 cooling capacity can be expected. This indicates that with three layers, a smaller value of ΔT provides a better cooling capability.

Using this data and relating it to the 45W load, Figure 4.2 can be generated. This calculation indicates that the more significant the ΔT requirement, the more severe the penalty in sizing of the device and overall financial cost this system will impose. This is particularly true since the curve appears to be exponential and that after approximately 54^{o}C severe penalties to area are obtained.

4.1.2. COP Versus Load

To obtain a better understanding of the influence of load on COP, graphs for the varying ΔTs are plotted as seen in Figure 4.3. As evident from the data, the COP falls dramatically with an increase in ΔT. This is an expected finding based on the background of TE operation.

For better understanding on the impact this has on the sizing of the TE modules, Figure 4.4 was composed. From this figure, an obvious optimum load area exists to obtain maximum COP. This should establish a sizing of the device based on the final deciding ΔT.

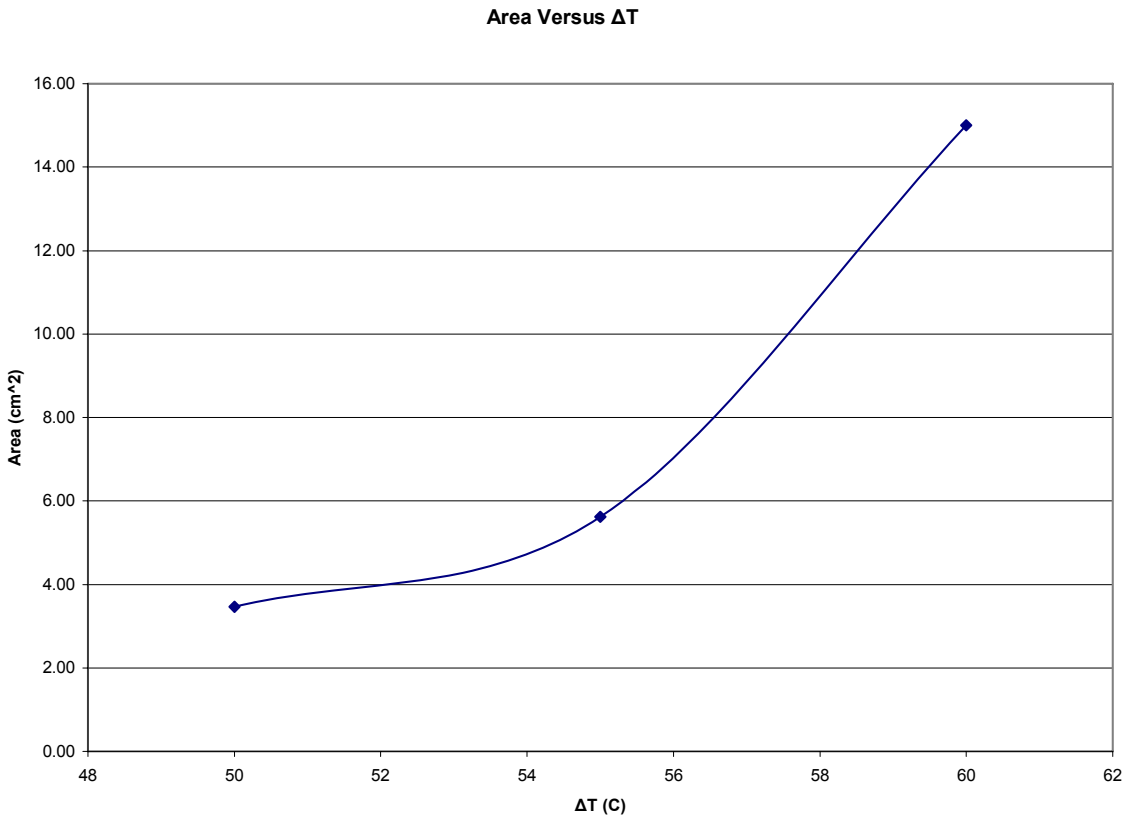


Figure 4.2. Area versus ΔT for three layers.

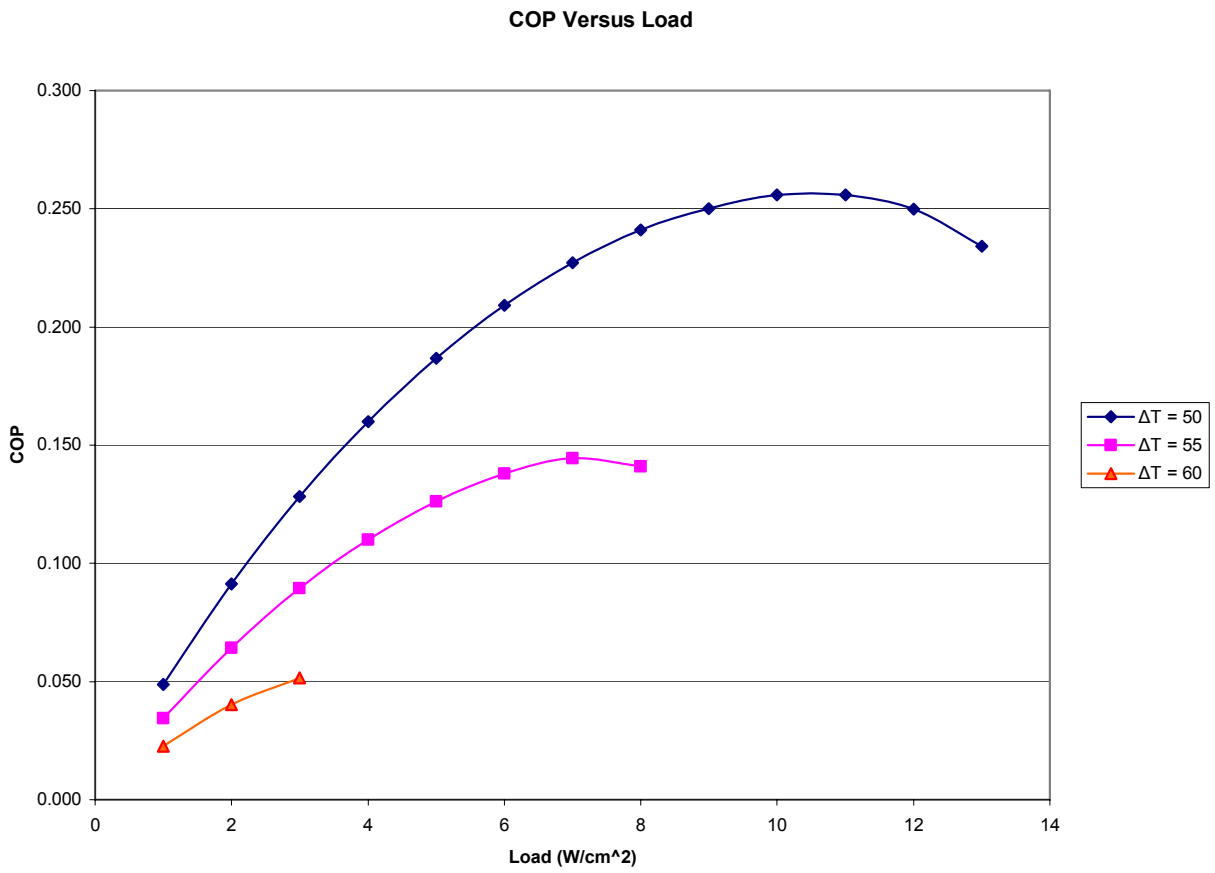


Figure 4.3. COP versus load for three layers.

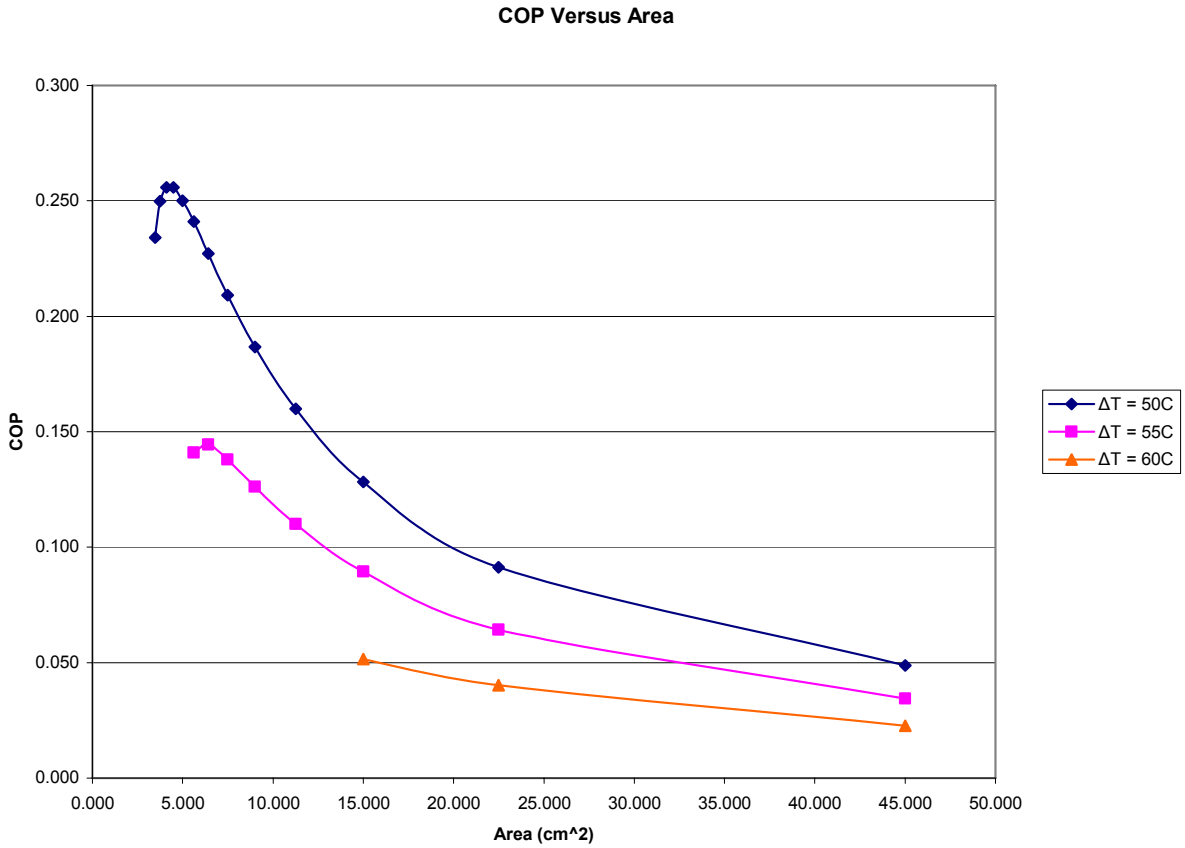


Figure 4.4 COP verus area for three layers.

4.1.3. Optimum ΔT Combinations

To acquire a full comprehension on any relevant patterns in layer optimization, Table 4.1 was constructed. Table 4.1 contains the optimum ΔT per layer for each specific overall ΔT.

One key observation that can be made from this table is that lower values of ΔT are at the initial layers and that a progressive increase in ΔT appears with each layer. This is logical. In choosing a large ΔT for the first layer, a large input power will result that must be cooled in the following layers. This in turn reduces the overall COP.

Another realization is that the ΔT per each layer is relatively close. No large swings in ΔT at each layer exist. Again, this goes back to the idea that a large ΔT demands a large input power that ultimately lowers the COP.

4.2. Four Layers

This design could have been halted at three layers. The goal of 45W cooling was met with a minimum ΔT of 50^{o}C. Nevertheless, the maximum COP of 0.256 at a ΔT of 50^{o}C is extremely low. Hence, four layers were placed under consideration to identify

Table 4.1. ΔT per layer for three layers.

ΔT	50C	55C	60C
1st Layer	16	17	19
2nd Layer	17	19	21
3rd Layer	17	19	20

any gains in increasing the number of layers.

As performed with three layers, COP, ΔT, load, and area relationships will be established.

4.2.1. Maximum Cooling Capacity Versus ΔT

Again, during data collection, a maximum overall loading was discovered for each ΔT. This maximum loading limit in terms of ΔT also appears to be to some extent linear as seen in Figure 4.5. In this case, the slope appears to be approximately 0.75W/(cm^2 ^{o}C). Therefore, for every 1 ^{o}C drop in the ΔT, an increase of 0.75W/cm^2 cooling capacity can be expected.

Using this data and relating it to the 45W load, Figure 4.6 can be generated. Similar to the three layer configuration, the observation that an increase in the ΔT requirement leads to severe penalties in sizing of the device can be made.

4.2.2. COP Versus Load

As done with the three layers investigation, a graph relating COP to load was constructed as seen in Figure 4.7. As noted with three layers, the COP falls dramatically with an increase in ΔT.

To better illustrate the influence COP has on the sizing of the TE modules, Figure 4.8 was contrived. As before, an optimum area appears to exist for each ΔT in terms of the COP.

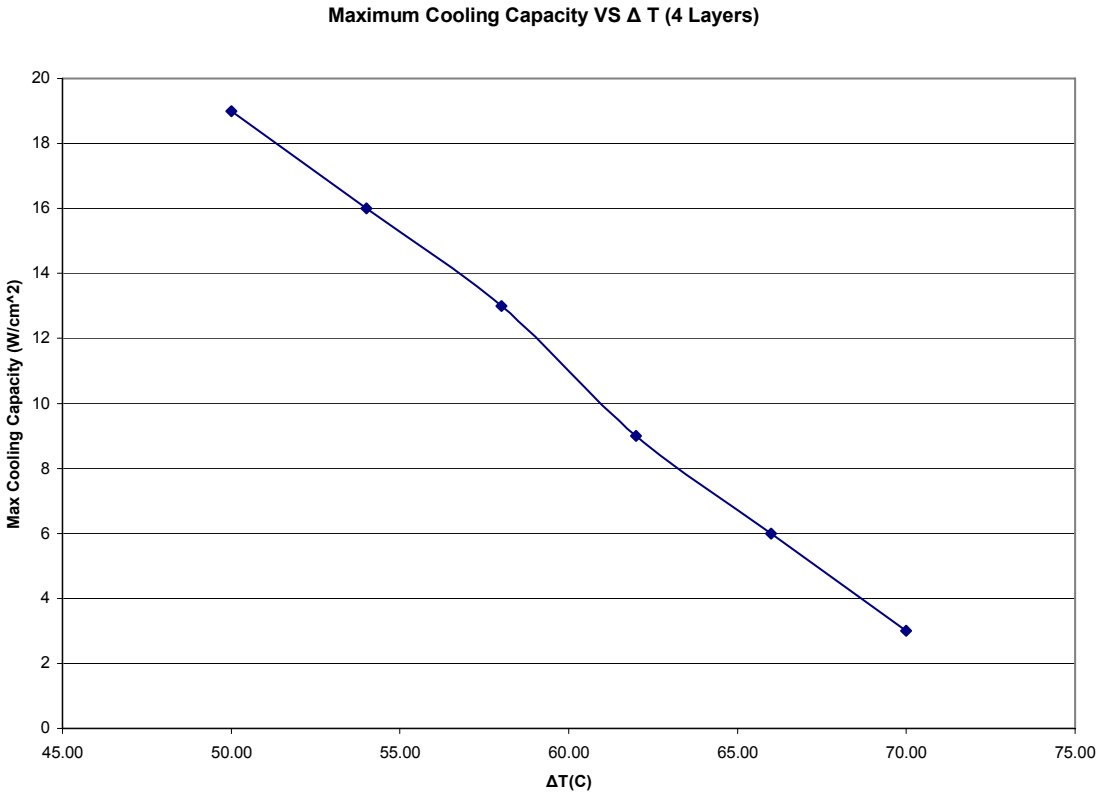


Figure 4.5. Max cooling capability versus ΔT for four layers

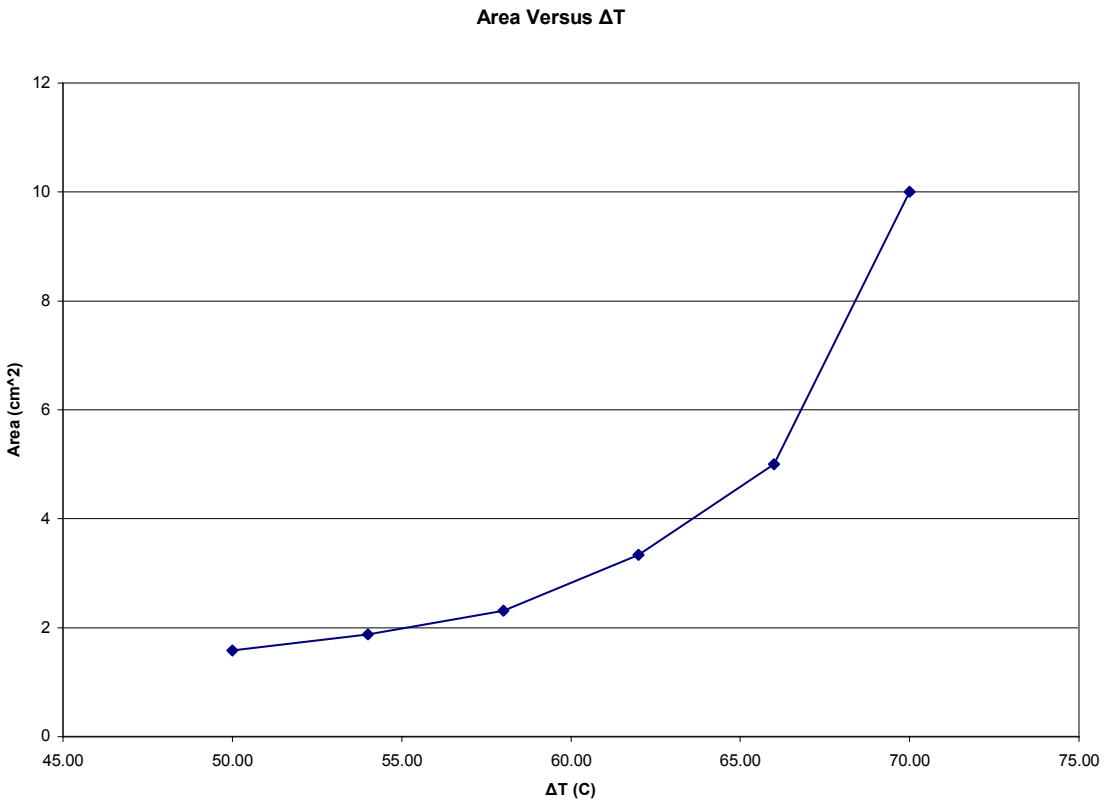


Figure 4.6. Area versus ΔT for four layers.

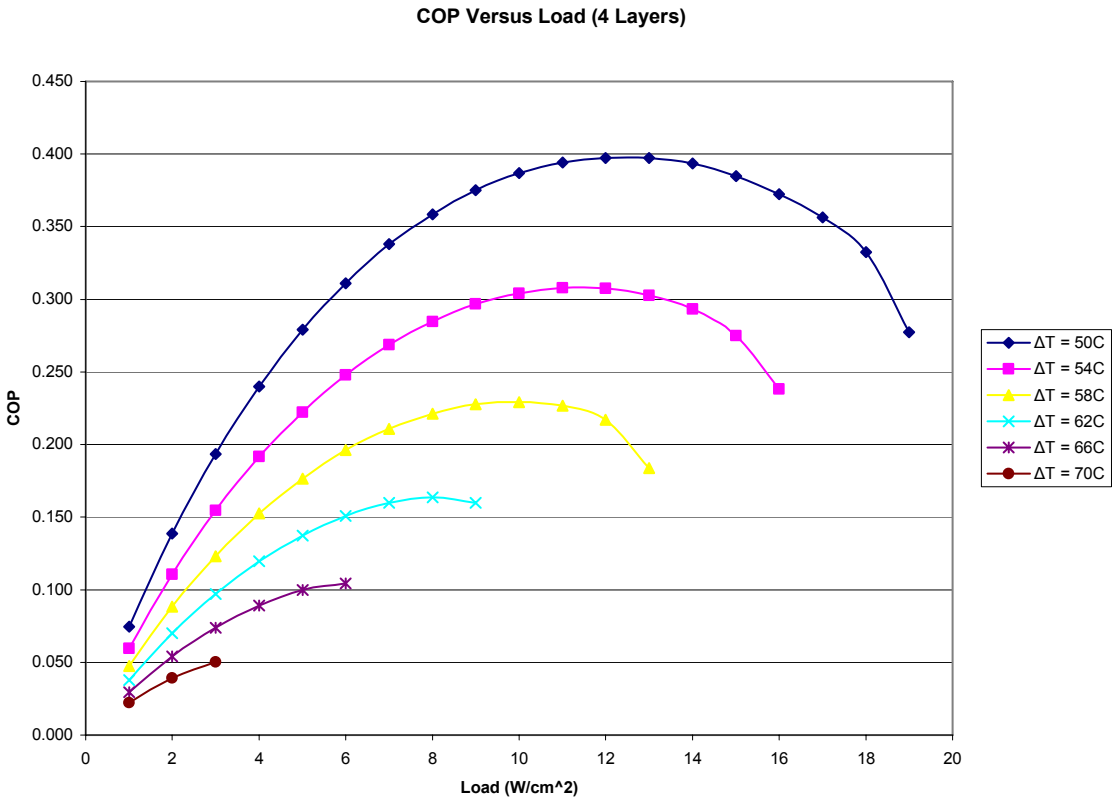


Figure 4.7. COP versus load for four layers.

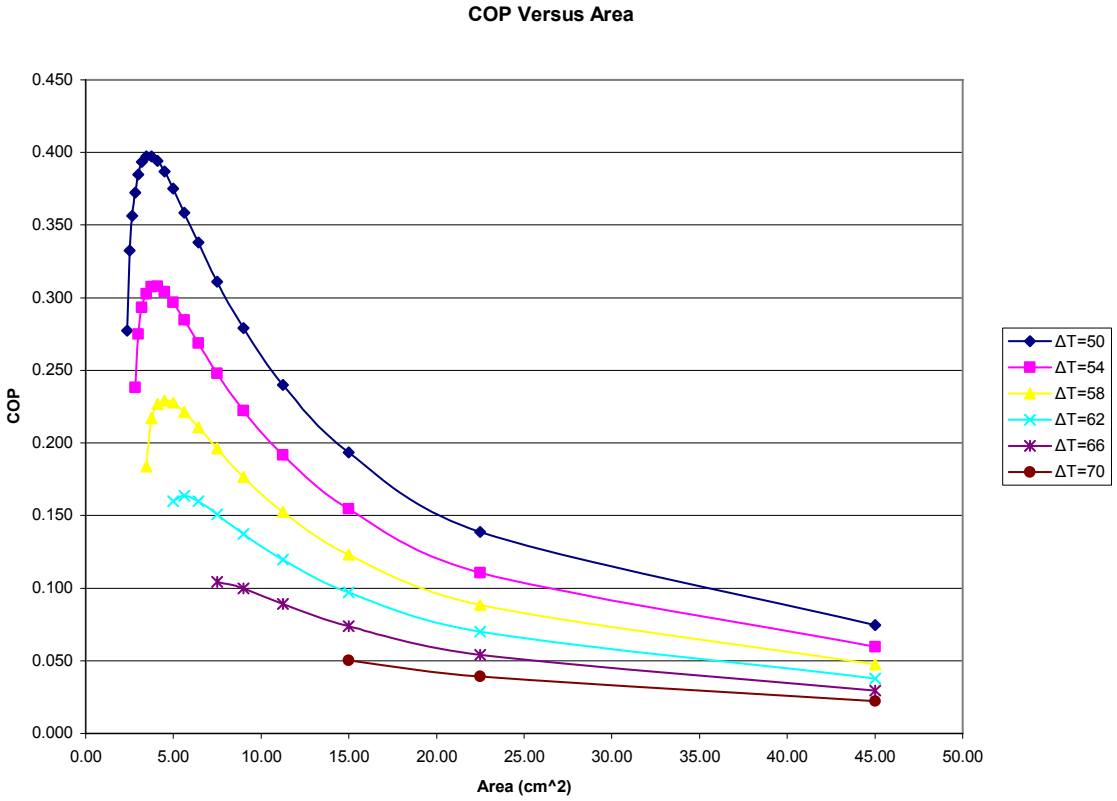


Figure 4.8. COP versus area for four layers.

4.2.3. Optimum ΔT Combinations

As accomplished with three layers, a table relating the optimum ΔT combinations per layer compared to an overall ΔT was constructed as seen in Table 4.2. As noted before, a progressive increase in the value of ΔT from the initial to end layers is apparent.

4.3. Comparison

A close examination of the differences in three and four layer TE systems shows that an increase in the number of layers has multiple justifications. First, increasing the number results in an overall larger maximum ΔT. With three layers, the maximum ΔT is expected to be 63 ^{o}C, while with four layers a maximum ΔT of 74^{o}C is obtained. Obviously using three layers at a ΔT of 63 ^{o}C or our four layers at a ΔT of 74^{o}C is moot, since the maximum cooling capacity at these ΔT values is zero, but this gives a good indication on the capacity of the layers.

A second argument for increasing the number of layers is the increase in performance. At a ΔT of 50^{o}C a maximum COP of 0.256 is obtained with three layers and 0.397 with four layers. This is an increase in performance by a factor of 1.55.

Table 4.2 ΔT per layer for four layers.

Delta T	50C	54C	58C	62C	66C	70C
1st Layer	12	12	14	14	14	16
2nd Layer	12	14	14	16	16	18
3rd Layer	12	14	14	16	18	18
4th Layer	14	14	16	16	18	18

Last, surprisingly there actually is a decrease in the surface area in terms of the maximum COP with increasing the number of layers. Again, at 50^{o}C an area of 15.54cm^{2} is obtained with three layers while an area of 13.15cm^{2} is concluded with four layers. Undeniably this observation is partially insignificant since another layer in itself adds more surface area. Yet, this reveals that an increase in performance goes a long way in helping reduce cost.

4.4 Summary

In this chapter the differences in ΔT, COP, loading, and area between three and four layers was examined. Performance, ΔT, and load enhancements were gained through moving from three to four layers. The only sacrifice made is cost, in that more devices will be necessitated for the additional layer.

In the next chapter, a final solution will be presented. An overview of what knowledge was gained from the simulation data will be discussed. Last, work that should be conducted in the future will be introduced.

Chapter 5

CONCLUSION AND FUTURE WORK

5.1 Conclusion

From the last chapter, several observations were made concerning an increase in layers. A layer increase results in higher COP, a larger maximum ΔT, and a smaller area requirement per layer. Yet, the gain in TE surface area per layer does not make up for the addition of a layer. Hence, although gains are made, a large increase in cost comes with these gains. This is particularly true with the TE module under examination. A $1cm^2$ area of this device can cost upwards of $4,000 with current manufacturing technology.

One of the main dilemmas in the assumption of the capacitors as a heat load is inconsistency. Although, the maximum current ripple heat load was determined, this value will rarely be the operational point. The inverter will scarcely ever be pushed to its limits and therefore the heat load will never be reached. Nevertheless, this heat load must be assumed to be the worst case scenario for practical reasons.

Based on the data collected, the optimum choice is to choose four layers with the minimum ΔT required, or 50^oC. Although, the data is based on maximum heat load of 45W, this gives room for the ΔT to increase with a lower load. For example, consider the area for maximum COP at 50^oC is $3.46cm^2$. If the load is reduced to 50%, for the same area, the ΔT can increase to 62^oC. A further reduction of load to 25% results in an increase of ΔT to 66^oC. Neverthless in terms of COP, operation of the TE device should be fixed at a ΔT at 50^oC for maximum COP.

Another issue that exists is the TE area that is required. The surface area of the capacitors chosen is relatively large. A 3.46cm^2 TE matrix will only provide cooling to a single location. Hence, either the surface area of the TE devices needs to be increased, adding significant cost and reducing the COP, or a thermal packaging material must be applied to the capacitors granting a small cooling surface.

Regardless of the data presented, the reality is that a COP of 0.397 is still too small to be of significant promise compared to other cooling technologies. Advancements in TE technology must still be made before adequate exposure of TE technology to cooling PEs can be achieved. If small ΔT requirements are part of the project description, then TE devices are a possible solution, but only for low cooling demands.

5.2 Future Work

Although three and four layers were placed under consideration, and some interesting findings were presented, another layer might further increase the maximum ΔT and COP limits. Ultimately there exists a limit to which gains will no longer be made. Future work should be performed to find this limit and compare the COP and ΔT gains to the increase in area of the TE devices.

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Appendices

Appendix I

THERMOELECTRIC MODEL

```
%%%%%%%%%%%% Thermoelectric (Advanced Thermoelectrics)
%%%%%%%%%%  ST-127-1.4-8.5


clear all;
clc;

SA = 4800*10^-6 * 4800 *10^-6 * 100^2 %cm2
N = 140;
H = .083;
L = .065;
W = .065;
Ratio = (L*W)/H;  %Area/length in
Ratio = Ratio*2.54; %length in cm
Ratio = .056 %.055


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%% DETERMING T VS R, alpha, K %%%%%%%%%%%%%%%%%%%%%%%%%

Alpha_n = -[209, 213, 210, 201, 187, 171, 161];
Resistivity_n = [2.38, 2.61, 2.79, 2.9, 2.94, 2.92, 2.88];
Thermal_Cond_n = [8, 8.23, 8.72, 9.8, 10.92, 12.07, 12.78];
Alpha_p = [173, 185, 194, 200, 203, 204, 202];
Resistivity_p = [.927, 1.015, 1.198, 1.415, 1.632, 1.834, 2.016];
Thermal_Cond_p = [9.63, 9.85, 9.87, 9.79, 9.7, 9.71, 9.92];
Temp_n = [298, 323, 348, 373, 398, 423, 438];
Temp_p = [298, 323, 348, 373, 398, 423, 448];
alpha_coef_n = polyfit(Temp_n,Alpha_n,3)
resist_coef_n = polyfit(Temp_n,Resistivity_n,3)
thermal_coef_n = polyfit (Temp_n,Thermal_Cond_n,3)
alpha_coef_p = polyfit(Temp_p,Alpha_p,3)
resist_coef_p = polyfit(Temp_p,Resistivity_p,3)
thermal_coef_p = polyfit (Temp_p,Thermal_Cond_p,3)

alpha_n=polyval(alpha_coef_n,Temp_n) ;
alpha_p=polyval(alpha_coef_p,Temp_p) ;
resistivity_n=polyval(resist_coef_n,Temp_n) ;
resistivity_p=polyval(resist_coef_p,Temp_p) ;
thermal_cond_n=polyval(thermal_coef_n,Temp_n)  ;
thermal_cond_p=polyval(thermal_coef_p,Temp_p)  ;


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
maxDeltaT = 50;
Qin = 16
Th = 120 + 273;

DeltaT1 = 4:2:16;
DeltaT2 = 4:2:16;
DeltaT3 = 4:2:16;
DeltaT4 = 4:2:16;

store = 0;
first = 0;
while first < length(DeltaT1)
    first = first + 1;
    second = 0;
    while second < length(DeltaT2)
        second = second + 1;
        third = 0;
        while third < length(DeltaT3)
            third = third + 1;
            fourth = 0;
            while fourth < length(DeltaT4)
                fourth = fourth + 1;
                overallT = DeltaT1(first) + DeltaT2(second) +
DeltaT3(third)+ DeltaT4(fourth);
                    if overallT == maxDeltaT;
                        store = store + 1;
                        DeltaT(store,1) = DeltaT1(first);
                        DeltaT(store,2) = DeltaT2(second);
                        DeltaT(store,3) = DeltaT3(third);
                        DeltaT(store,4) = DeltaT4(fourth);
                    end;
            end;
        end;
    end;
end;


current = 0:.001:2.5;
Ic=ones(1,length(current));

i = 0;
while i < length(DeltaT(:,1))
    i = i + 1;

    %%%%%% FIRST LAYER %%%%%

    Tc_1 = Th - DeltaT(i,1);
    tave = (Th + Tc_1)/2;

alpha_new_n=(polyval(alpha_coef_n,Tc_1)+polyval(alpha_coef_n,Tc_1+Delta
T(i,1)/6)+...
```

```
polyval(alpha_coef_n,Tc_1+DeltaT(i,1)*2/6)+polyval(alpha_coef_n,Tc_1+De
ltaT(i,1)*3/6)+...

polyval(alpha_coef_n,Tc_1+DeltaT(i,1)*4/6)+polyval(alpha_coef_n,Tc_1+De
ltaT(i,1)*5/6)+...
    polyval(alpha_coef_n,Tc_1+DeltaT(i,1)))/7;

alpha_new_p=(polyval(alpha_coef_p,Tc_1)+polyval(alpha_coef_p,Tc_1+Delta
T(i,1)/6)+...

polyval(alpha_coef_p,Tc_1+DeltaT(i,1)*2/6)+polyval(alpha_coef_p,Tc_1+De
ltaT(i,1)*3/6)+...

polyval(alpha_coef_p,Tc_1+DeltaT(i,1)*4/6)+polyval(alpha_coef_p,Tc_1+De
ltaT(i,1)*5/6)+...
    polyval(alpha_coef_p,Tc_1+DeltaT(i,1)))/7;

resistivity_new_n=(polyval(resist_coef_n,Tc_1)+polyval(resist_coef_n,Tc
_1+DeltaT(i,1)/6)+...

polyval(resist_coef_n,Tc_1+DeltaT(i,1)*2/6)+polyval(resist_coef_n,Tc_1+
DeltaT(i,1)*3/6)+...

polyval(resist_coef_n,Tc_1+DeltaT(i,1)*4/6)+polyval(resist_coef_n,Tc_1+
DeltaT(i,1)*5/6)+...
    polyval(resist_coef_n,Tc_1+DeltaT(i,1)))/7;

resistivity_new_p=(polyval(resist_coef_p,Tc_1)+polyval(resist_coef_p,Tc
_1+DeltaT(i,1)/6)+...

polyval(resist_coef_p,Tc_1+DeltaT(i,1)*2/6)+polyval(resist_coef_p,Tc_1+
DeltaT(i,1)*3/6)+...

polyval(resist_coef_p,Tc_1+DeltaT(i,1)*4/6)+polyval(resist_coef_p,Tc_1+
DeltaT(i,1)*5/6)+...
    polyval(resist_coef_p,Tc_1+DeltaT(i,1)))/7;

thermal_cond_new_n=(polyval(thermal_coef_n,Tc_1)+polyval(thermal_coef_n
,Tc_1+DeltaT(i,1)/6)+...

polyval(thermal_coef_n,Tc_1+DeltaT(i,1)*2/6)+polyval(thermal_coef_n,Tc_
1+DeltaT(i,1)*3/6)+...

polyval(thermal_coef_n,Tc_1+DeltaT(i,1)*4/6)+polyval(thermal_coef_n,Tc_
1+DeltaT(i,1)*5/6)+...
    polyval(thermal_coef_n,Tc_1+DeltaT(i,1)))/7;

thermal_cond_new_p=(polyval(thermal_coef_p,Tc_1)+polyval(thermal_coef_p
,Tc_1+DeltaT(i,1)/6)+...

polyval(thermal_coef_p,Tc_1+DeltaT(i,1)*2/6)+polyval(thermal_coef_p,Tc_
1+DeltaT(i,1)*3/6)+...
```

```
polyval(thermal_coef_p,Tc_1+DeltaT(i,1)*4/6)+polyval(thermal_coef_p,Tc_
1+DeltaT(i,1)*5/6)+...
    polyval(thermal_coef_p,Tc_1+DeltaT(i,1)))/7;

A = (alpha_new_p-alpha_new_n)*1e-6;
K = (Ratio*thermal_cond_new_n + Ratio*thermal_cond_new_p)*1e-3*4.2;
R = (1/Ratio.*resistivity_new_n+1/Ratio.*resistivity_new_p)*1e-3;

Q = N*(A*Tc_1*current- K*DeltaT(i,1)- R*current.^2/2)/SA;
V = N*(A*DeltaT(i,1)+R*current);

% figure(1)
% plot (current,Q)
% axis ([0 2.5 0 90])

 j = 0;
 while j < length(Q)
     j = j + 1;
     if Q(j) > Qin
         cooling_pos = j;
         break;
     else
         cooling_pos = 0;
     end;
 end;

if cooling_pos == 0
Vin(i) = 0;
Iin(i) = 0;
Pin(i) = 0;

else
Vin(i) = V(cooling_pos);
Iin(i) = current(cooling_pos);
Pin(i) = Iin(i)*Vin(i);

end;

Qin2 = Pin(i) + Qin;

%%%%%% SECOND LAYER %%%%%

    Tc_2 = Tc_1 - DeltaT(i,2);
    tave = (Tc_1 + Tc_2)/2;

alpha_new_n=(polyval(alpha_coef_n,Tc_2)+polyval(alpha_coef_n,Tc_2+Delta
T(i,2)/6)+...

polyval(alpha_coef_n,Tc_2+DeltaT(i,2)*2/6)+polyval(alpha_coef_n,Tc_2+De
ltaT(i,2)*3/6)+...
```

```
polyval(alpha_coef_n,Tc_2+DeltaT(i,2)*4/6)+polyval(alpha_coef_n,Tc_2+De
ltaT(i,2)*5/6)+...
    polyval(alpha_coef_n,Tc_2+DeltaT(i,2)))/7;

alpha_new_p=(polyval(alpha_coef_p,Tc_2)+polyval(alpha_coef_p,Tc_2+Delta
T(i,2)/6)+...

polyval(alpha_coef_p,Tc_2+DeltaT(i,2)*2/6)+polyval(alpha_coef_p,Tc_2+De
ltaT(i,2)*3/6)+...

polyval(alpha_coef_p,Tc_2+DeltaT(i,2)*4/6)+polyval(alpha_coef_p,Tc_2+De
ltaT(i,2)*5/6)+...
    polyval(alpha_coef_p,Tc_2+DeltaT(i,2)))/7;

resistivity_new_n=(polyval(resist_coef_n,Tc_2)+polyval(resist_coef_n,Tc
_2+DeltaT(i,2)/6)+...

polyval(resist_coef_n,Tc_2+DeltaT(i,2)*2/6)+polyval(resist_coef_n,Tc_2+
DeltaT(i,2)*3/6)+...

polyval(resist_coef_n,Tc_2+DeltaT(i,2)*4/6)+polyval(resist_coef_n,Tc_2+
DeltaT(i,2)*5/6)+...
    polyval(resist_coef_n,Tc_2+DeltaT(i,2)))/7;

resistivity_new_p=(polyval(resist_coef_p,Tc_2)+polyval(resist_coef_p,Tc
_2+DeltaT(i,2)/6)+...

polyval(resist_coef_p,Tc_2+DeltaT(i,2)*2/6)+polyval(resist_coef_p,Tc_2+
DeltaT(i,2)*3/6)+...

polyval(resist_coef_p,Tc_2+DeltaT(i,2)*4/6)+polyval(resist_coef_p,Tc_2+
DeltaT(i,2)*5/6)+...
    polyval(resist_coef_p,Tc_2+DeltaT(i,2)))/7;

thermal_cond_new_n=(polyval(thermal_coef_n,Tc_2)+polyval(thermal_coef_n
,Tc_2+DeltaT(i,2)/6)+...

polyval(thermal_coef_n,Tc_2+DeltaT(i,2)*2/6)+polyval(thermal_coef_n,Tc_
2+DeltaT(i,2)*3/6)+...

polyval(thermal_coef_n,Tc_2+DeltaT(i,2)*4/6)+polyval(thermal_coef_n,Tc_
2+DeltaT(i,2)*5/6)+...
    polyval(thermal_coef_n,Tc_2+DeltaT(i,2)))/7;

thermal_cond_new_p=(polyval(thermal_coef_p,Tc_2)+polyval(thermal_coef_p
,Tc_2+DeltaT(i,2)/6)+...

polyval(thermal_coef_p,Tc_2+DeltaT(i,2)*2/6)+polyval(thermal_coef_p,Tc_
2+DeltaT(i,2)*3/6)+...

polyval(thermal_coef_p,Tc_2+DeltaT(i,2)*4/6)+polyval(thermal_coef_p,Tc_
2+DeltaT(i,2)*5/6)+...
    polyval(thermal_coef_p,Tc_2+DeltaT(i,2)))/7;
```

```
A = (alpha_new_p-alpha_new_n)*1e-6;
K = (Ratio*thermal_cond_new_n + Ratio*thermal_cond_new_p)*1e-3*4.2;
R = (1/Ratio.*resistivity_new_n+1/Ratio.*resistivity_new_p)*1e-3;

Q2 = N*(A*Tc_2*current- K*DeltaT(i,2)- R*current.^2/2)/SA;
V2 = N*(A*DeltaT(i,2)+R*current);

% figure(2)
% plot (current,Q2)
% axis ([0 2.5 0 90])

j = 0;
 while j < length(Q2)
     j = j + 1;
     if Q2(j) > Qin2
         cooling_pos = j;
         break;
     else
         cooling_pos = 0;
     end;
 end;

if cooling_pos == 0

    Vin2(i) = 0;
    Iin2(i) = 0;
    Pin2(i) = 0;

else
    Vin2(i) = V2(cooling_pos);
    Iin2(i) = current(cooling_pos);
    Pin2(i) = Iin2(i)*Vin2(i);

end;

Qin3 = Pin2(i) + Qin2;

%%%%%% THIRD LAYER %%%%%

    Tc_3 = Tc_2 - DeltaT(i,3);
    tave = (Tc_2 + Tc_3)/2;

alpha_new_n=(polyval(alpha_coef_n,Tc_3)+polyval(alpha_coef_n,Tc_3+Delta
T(i,3)/6)+...

polyval(alpha_coef_n,Tc_3+DeltaT(i,3)*2/6)+polyval(alpha_coef_n,Tc_3+De
ltaT(i,3)*3/6)+...

polyval(alpha_coef_n,Tc_3+DeltaT(i,3)*4/6)+polyval(alpha_coef_n,Tc_3+De
ltaT(i,3)*5/6)+...
    polyval(alpha_coef_n,Tc_3+DeltaT(i,3)))/7;
```

```
alpha_new_p=(polyval(alpha_coef_p,Tc_3)+polyval(alpha_coef_p,Tc_3+Delta
T(i,3)/6)+...

polyval(alpha_coef_p,Tc_3+DeltaT(i,3)*2/6)+polyval(alpha_coef_p,Tc_3+De
ltaT(i,3)*3/6)+...

polyval(alpha_coef_p,Tc_3+DeltaT(i,3)*4/6)+polyval(alpha_coef_p,Tc_3+De
ltaT(i,3)*5/6)+...
    polyval(alpha_coef_p,Tc_3+DeltaT(i,3)))/7;

resistivity_new_n=(polyval(resist_coef_n,Tc_3)+polyval(resist_coef_n,Tc
_3+DeltaT(i,3)/6)+...

polyval(resist_coef_n,Tc_3+DeltaT(i,3)*2/6)+polyval(resist_coef_n,Tc_3+
DeltaT(i,3)*3/6)+...

polyval(resist_coef_n,Tc_3+DeltaT(i,3)*4/6)+polyval(resist_coef_n,Tc_3+
DeltaT(i,3)*5/6)+...
    polyval(resist_coef_n,Tc_3+DeltaT(i,3)))/7;

resistivity_new_p=(polyval(resist_coef_p,Tc_3)+polyval(resist_coef_p,Tc
_3+DeltaT(i,3)/6)+...

polyval(resist_coef_p,Tc_3+DeltaT(i,3)*2/6)+polyval(resist_coef_p,Tc_3+
DeltaT(i,3)*3/6)+...

polyval(resist_coef_p,Tc_3+DeltaT(i,3)*4/6)+polyval(resist_coef_p,Tc_3+
DeltaT(i,3)*5/6)+...
    polyval(resist_coef_p,Tc_3+DeltaT(i,3)))/7;

thermal_cond_new_n=(polyval(thermal_coef_n,Tc_3)+polyval(thermal_coef_n
,Tc_3+DeltaT(i,3)/6)+...

polyval(thermal_coef_n,Tc_3+DeltaT(i,3)*2/6)+polyval(thermal_coef_n,Tc_
3+DeltaT(i,3)*3/6)+...

polyval(thermal_coef_n,Tc_3+DeltaT(i,3)*4/6)+polyval(thermal_coef_n,Tc_
3+DeltaT(i,3)*5/6)+...
    polyval(thermal_coef_n,Tc_3+DeltaT(i,3)))/7;

thermal_cond_new_p=(polyval(thermal_coef_p,Tc_3)+polyval(thermal_coef_p
,Tc_3+DeltaT(i,3)/6)+...

polyval(thermal_coef_p,Tc_3+DeltaT(i,3)*2/6)+polyval(thermal_coef_p,Tc_
3+DeltaT(i,3)*3/6)+...

polyval(thermal_coef_p,Tc_3+DeltaT(i,3)*4/6)+polyval(thermal_coef_p,Tc_
3+DeltaT(i,3)*5/6)+...
    polyval(thermal_coef_p,Tc_3+DeltaT(i,3)))/7;

A = (alpha_new_p-alpha_new_n)*1e-6;
K = (Ratio*thermal_cond_new_n + Ratio*thermal_cond_new_p)*1e-3*4.2;
R = (1/Ratio.*resistivity_new_n+1/Ratio.*resistivity_new_p)*1e-3;
```

```
Q3 = N*(A*Tc_3*current- K*DeltaT(i,3)- R*current.^2/2)/SA;
V3 = N*(A*DeltaT(i,3)+R*current);

% figure(3)
% plot (current,Q3)
% axis ([0 2.5 0 90])

 j = 0;
 while j < length(Q3)
     j = j + 1;
     if Q3(j) > Qin3
         cooling_pos = j;
         break;
     else
         cooling_pos = 0;
     end;
 end;

if cooling_pos == 0

    Vin3(i) = 0;
    Iin3(i) = 0;
    Pin3(i) = 0;

else
    Vin3(i) = V3(cooling_pos);
    Iin3(i) = current(cooling_pos);
    Pin3(i) = Iin3(i)*Vin3(i);

end;

Qin4 = Pin3(i) + Qin3;

%%%%%% FOURTH LAYER %%%%%

    Tc_4 = Tc_3 - DeltaT(i,4);
    tave = (Tc_4 + Tc_3)/2;

alpha_new_n=(polyval(alpha_coef_n,Tc_4)+polyval(alpha_coef_n,Tc_4+Delta
T(i,4)/6)+...

polyval(alpha_coef_n,Tc_4+DeltaT(i,4)*2/6)+polyval(alpha_coef_n,Tc_4+De
ltaT(i,4)*3/6)+...

polyval(alpha_coef_n,Tc_4+DeltaT(i,4)*4/6)+polyval(alpha_coef_n,Tc_4+De
ltaT(i,4)*5/6)+...
    polyval(alpha_coef_n,Tc_4+DeltaT(i,4)))/7;

alpha_new_p=(polyval(alpha_coef_p,Tc_4)+polyval(alpha_coef_p,Tc_4+Delta
T(i,4)/6)+...
```

```
polyval(alpha_coef_p,Tc_4+DeltaT(i,4)*2/6)+polyval(alpha_coef_p,Tc_4+De
ltaT(i,4)*3/6)+...

polyval(alpha_coef_p,Tc_4+DeltaT(i,4)*4/6)+polyval(alpha_coef_p,Tc_4+De
ltaT(i,4)*5/6)+...
    polyval(alpha_coef_p,Tc_4+DeltaT(i,4)))/7;

resistivity_new_n=(polyval(resist_coef_n,Tc_4)+polyval(resist_coef_n,Tc
_4+DeltaT(i,4)/6)+...

polyval(resist_coef_n,Tc_4+DeltaT(i,4)*2/6)+polyval(resist_coef_n,Tc_4+
DeltaT(i,4)*3/6)+...

polyval(resist_coef_n,Tc_4+DeltaT(i,4)*4/6)+polyval(resist_coef_n,Tc_4+
DeltaT(i,4)*5/6)+...
    polyval(resist_coef_n,Tc_4+DeltaT(i,4)))/7;

resistivity_new_p=(polyval(resist_coef_p,Tc_4)+polyval(resist_coef_p,Tc
_4+DeltaT(i,4)/6)+...

polyval(resist_coef_p,Tc_4+DeltaT(i,4)*2/6)+polyval(resist_coef_p,Tc_4+
DeltaT(i,4)*3/6)+...

polyval(resist_coef_p,Tc_4+DeltaT(i,4)*4/6)+polyval(resist_coef_p,Tc_4+
DeltaT(i,4)*5/6)+...
    polyval(resist_coef_p,Tc_4+DeltaT(i,4)))/7;

thermal_cond_new_n=(polyval(thermal_coef_n,Tc_4)+polyval(thermal_coef_n
,Tc_4+DeltaT(i,4)/6)+...

polyval(thermal_coef_n,Tc_4+DeltaT(i,4)*2/6)+polyval(thermal_coef_n,Tc_
4+DeltaT(i,4)*3/6)+...

polyval(thermal_coef_n,Tc_4+DeltaT(i,4)*4/6)+polyval(thermal_coef_n,Tc_
4+DeltaT(i,4)*5/6)+...
    polyval(thermal_coef_n,Tc_4+DeltaT(i,4)))/7;

thermal_cond_new_p=(polyval(thermal_coef_p,Tc_4)+polyval(thermal_coef_p
,Tc_4+DeltaT(i,4)/6)+...

polyval(thermal_coef_p,Tc_4+DeltaT(i,4)*2/6)+polyval(thermal_coef_p,Tc_
4+DeltaT(i,4)*3/6)+...

polyval(thermal_coef_p,Tc_4+DeltaT(i,4)*4/6)+polyval(thermal_coef_p,Tc_
4+DeltaT(i,4)*5/6)+...
    polyval(thermal_coef_p,Tc_4+DeltaT(i,4)))/7;

A = (alpha_new_p-alpha_new_n)*1e-6;
K = (Ratio*thermal_cond_new_n + Ratio*thermal_cond_new_p)*1e-3*4.2;
R = (1/Ratio.*resistivity_new_n+1/Ratio.*resistivity_new_p)*1e-3;

Q4 = N*(A*Tc_4*current- K*DeltaT(i,4)- R*current.^2/2)/SA;
V4 = N*(A*DeltaT(i,4)+R*current);
```

```
% figure(3)
% plot (current,Q3)
% axis ([0 2.5 0 90])

 j = 0;
 while j < length(Q4)
     j = j + 1;
     if Q4(j) > Qin4
         cooling_pos = j;
         break;
     else
         cooling_pos = 0;
     end;
 end;

if cooling_pos == 0

    Vin4(i) = 0;
    Iin4(i) = 0;
    Pin4(i) = 0;

else
    Vin4(i) = V4(cooling_pos);
    Iin4(i) = current(cooling_pos);
    Pin4(i) = Iin4(i)*Vin4(i);

end;

end;

k = 0;
z = 0;
while k < length (Pin)
    k = k + 1;
    if Pin(k) == 0
       z = z + 1;
    elseif Pin2(k) == 0
       z = z + 1;
    elseif Pin3(k) == 0
       z = z + 1;
    elseif Pin4(k) == 0
       z = z + 1;
    else
       Pin1_new(k-z) = Pin(k);
       Pin2_new(k-z) = Pin2(k);
       Pin3_new(k-z) = Pin3(k);
       Pin4_new(k-z) = Pin4(k);
       Vin1_new(k-z) = Vin(k);
       Vin2_new(k-z) = Vin2(k);
       Vin3_new(k-z) = Vin3(k);
       Vin4_new(k-z) = Vin4(k);
       Iin1_new(k-z) = Iin(k);
```

```
        Iin2_new(k-z) = Iin2(k);
        Iin3_new(k-z) = Iin3(k);
        Iin4_new(k-z) = Iin4(k);
        DeltaT1_new(k-z) = DeltaT(k,1);
        DeltaT2_new(k-z) = DeltaT(k,2);
        DeltaT3_new(k-z) = DeltaT(k,3);
        DeltaT4_new(k-z) = DeltaT(k,4);
    end;
end;

COP = Qin./(Pin1_new + Pin2_new + Pin3_new +Pin4_new)
COP_pos = find(max(COP) == COP)
clc;
Qin
max_COP = COP(COP_pos)
Pin1_opt = Pin1_new(COP_pos)
Pin2_opt = Pin2_new(COP_pos)
Pin3_opt = Pin3_new(COP_pos)
Pin4_opt = Pin4_new(COP_pos)
DeltaT1_opt = DeltaT1_new(COP_pos)
DeltaT2_opt = DeltaT2_new(COP_pos)
DeltaT3_opt = DeltaT3_new(COP_pos)
DeltaT4_opt = DeltaT4_new(COP_pos)
```

Vita:

Michael Starke began studying engineering in 2000. He received his Bachelors in Electrical Engineering at the University of Tennessee at Knoxville in 2004. Michael decided to continue his education and remained at the University of Tennessee in pursuit of Masters in Science in Electrical Engineering with the concentration of Power and Power Electronics. Michael received his Masters in August 2006. During his studies, he became employed Power Electronics and Electric Machinery Research Center at Oak Ridge National Laboratory to conduct research in cooling power electronics which lead to his thesis topic. Michael is currently continuing his education at the University of Tennessee through seeking a PHD in Electrical Engineering.