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Forearm cooling for intention tremor in multiple sclerosis

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ABSTRACT

Multiple sclerosis (MS) is an illness, which affects the immune system functionality in human body including spinal cord and brain. The MS symptoms include vision problems, difficulties in walking, fatigue, muscle spasms, ataxia and tremor. Medical research has shown that extracting heat from the patient's body through specialized subcutaneous vascular structures that underlie the non-hairy skin surfaces of the human body (upper limbs: the palms of the hands and forearms), improves performances for the daily activity of MS patients. Traditional techniques like cold-water bath or ice pack are used by MS patients but are not power intensive, portable or convenient. Therefore, it is vital to develop a biomedical-cooling device that is lightweight, effective and easy to use for MS patients.

This research project aims to investigate experimentally the feasibility of using peltier cooling technology to develop an efficient, lightweight, portable cooling device with no moving parts and no circulating liquids to be used by MS patients in daily life routines as well as in hospital environment. This aim was achieved through the following objectives:

- Develop an effective heat sink device capable of extracting the heat rejected by the peltier device through experimentally testing various heat sink configurations and testing various phase change materials (PCMs) at various power inputs of 0.5, 1, 1.5, 2, 3, 6 and 9 watts.
- Develop a multi peltier cooling module and characterise its cooling performance using PCM based heat sink.

In this research, two sets of experimental studies were carried out to identify temperature changes, the cooling rate and the power demand. The first set of experiments investigated various heat sink configurations to characterise the cooling performance of a single peltier device in terms of the cooling temperature, temperature at which heat is rejected, time duration through which cooling is achieved at various power inputs. The second set of experiments utilised three peltier devices with PCM based heat sink to characterise a cooling unit that forms the basic structure of the overall cooling device. The experiments involved testing the three peltier unit at various power inputs of 0.5, 1, 1.5, 2, 3, 6 and 9 watts and during cyclic operation.

Results of the single peltier testing showed that a PCM based heat sink is needed to absorb the heat rejected by the peltier device to achieve cooling temperature below 10°C for a period of 3600 sec. For the three peltier cooling unit, the use of PCM OM37 with 3Watt power input to the peltier produced cooling at low temperature of 15°C for a period of about 800 sec and with 6Watt the temperature decreased to 11.66°C after 1020 sec. The temperature of 11.66°C achieved by OM37P using 6 W is the lowest temperature attained compared to 3 and 9 W. For the cyclic operation, with 3 W power input, the device was able to maintain the temperature of the water box around 5°C below the ambient temperature and by applying 6 W, cooling will be produced only during the first cycle.

This research project investigated using the combination of peltiers with PCM materials to reduce the temperature to 11.66°C for period of 17 minutes, which can help to alleviate the symptoms of MS patients like intention tremor, heat intolerance and fatigue. The results illustrated that PCM OM37P with power input of 6 W to the thermoelectric coolers has the capability to attain such requirement.

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ABBREVIATION

AVAS	Arteriovenous anastomoses
CAD	Computer aided design
HSU	Heat storage unit
MS	Multiple sclerosis
PCM	Phase change material
PPMS	Primary progressive MS
PRMS	Progressive-relapsing MS
RRMS	Relapsing-remitting MS
SPMS	Secondary progressive MS
TEC	Thermoelectric cooler

NOMENCLATURE

Symbol	**Quantity**	**SI unit**
Δh_m	Heat of fusion per unit mass	J/kg
a_m	Fraction melted	NA
C_p	Specific heat capacity	J/kgk
$_{cap}$	Average specific heat between T_i and T_f	J/ kg k
c_{lp}	Average specific heat between T_m and T_f	J/ kg k
c_{sp}	Average specific heat between T_i and T_m	J/ kg k
COP	Coefficient of performance	NA
m	Mass of PCM	kg
T_i	Initial temperature	°C
T_f	Final temperature	**°C**
T_m	Melting temperature	**°C**

Chapter 1: *Introduction*

1.1 Introduction

Multiple sclerosis (MS) is an immune-mediated disease of the central nervous system (CNS), which attacks the myelinated axons in the CNS and destroys the axons and myelin [1-4]. It causes inflammation to brain and spinal cord and produces neurological disability in young adults [5, 6]. The etiology for MS is unknown, but it seems to contain a combination of genetic vulnerability and a non-genetic trigger such as environmental factors, virus and metabolism [7]. Symptoms such as vision problems, difficulties in walking, fatigue, muscle spasms, ataxia and tremor are often experienced in MS patients [2, 7, 8].

Around 75% of people with MS experience a tremor. Tremor is an alternating and involuntary movement that can affect the muscles of any part of the body [9]. There are two types of tremor, Intention and Postural tremor. Intention is characterised by a slow shaking that occurs at the end of an intended movement, most noticeably in the hands. It is also known as Kinetic and Action Tremor. MS Patients with Postural tremor experience jaw, lip or tongue tremor that may affect their ability to speak efficiently. It occurs when the limbs are outstretched [10-12]. When the temperature or heat in the body increases, symptoms will get worse temporarily. There is no known cure for MS, but the effects of manipulating the internal thermal condition of MS patients have been noted previously [13]. One useful method is extracting heat from the patient's body through specialized subcutaneous vascular structures that underlie the non-hairy skin surfaces of the human body on their upper limbs; hand and forearm that improves MS patient's daily life performances. Blood flow through these specialized vascular structures supply a mean for heat accumulated within the body to be transferred efficiently to the external environment [14]. As conclusion of a test carried out by Granh et al. the cooling via one hand improves the physical performance in heat-sensitive MS patients [15]. Hand cooling was found by Goosey-Tolfrey et al. to be effective in temperature reduction for after-exercise hyperthermia applied to wheelchair and able-bodied athletes [16].

Published medical research by Feys P et al. based on clinical trials showed that cooling the forearm outer skin down to 18°C for period of 15 minutes can reduce tremor. It also illustrated that tremor reduction continued throughout 30-minute post cooling evaluation phase [17].

Ice water bath or ice pack is the most commonly used cooling technique. As the ice melts and loses its cooling capability, it can't maintain the cooling effect for the time required by the MS patients. So an efficient cooling device that can work continuously is needed for the individuals who suffer from MS.

There are a number of cooling technologies that are used in various applications including mechanical vapour compression, vapour sorption, magnetic, acoustic and thermoelectric cooling devices. Mechanical vapour compression and vapour sorption cooling systems involve the use of compressors or pumps to circulate the working fluids hence they pause risks associated with the use of moving parts and the leakage of working fluids. Magnetic and acoustic cooling technologies are still in the research phase and hence no commercial supplier of such devices is currently available. Peltier or Thermoelectric coolers have been used to provide cooling in many applications including electronic devices. These coolers use the peltier or thermoelectric effect, which creates voltage when there is a temperature difference. Also when a voltage is applied to semiconductor material, it produces temperature difference contrariwise [18]. Peltiers are small in size, lightweight and do not have any moving parts so they don't make noise, need less maintenance and are portable. They are low in cost and do not have any circulating fluid. As long as a fixed voltage is supplied, peltiers can produce steady cooling performances that can last for several hours.

Peltier cooling has been used for some applications such as small size coolers in the market and electronic cooling like in Lab-on-a-Chip (LOC) technology that allows compactness and faster analysis in medical diagnostic. Peltier elements can be used to temper electronic circuits or base plates but they have not been used for MS patients cooling [19].

1.2 Aims and objectives

The aim of this research project is to experimentally investigate the use of peltier cooling devices to develop an efficient, light weight, compact and portable cooling device with no moving parts and no circulating fluids to be used by MS patients (see figures 1.1 and 1.2). This can be achieved through the following objectives:

(i) Characterise experimentally the cooling performance of a single peltier cooling device using various heat sink configurations and using phase change material

(ii) Characterise experimentally a multi peltier cooling module consisting of three peltiers and PCM based heat sink and

(iii) Investigate the performance of the cooling module during cyclic operation.

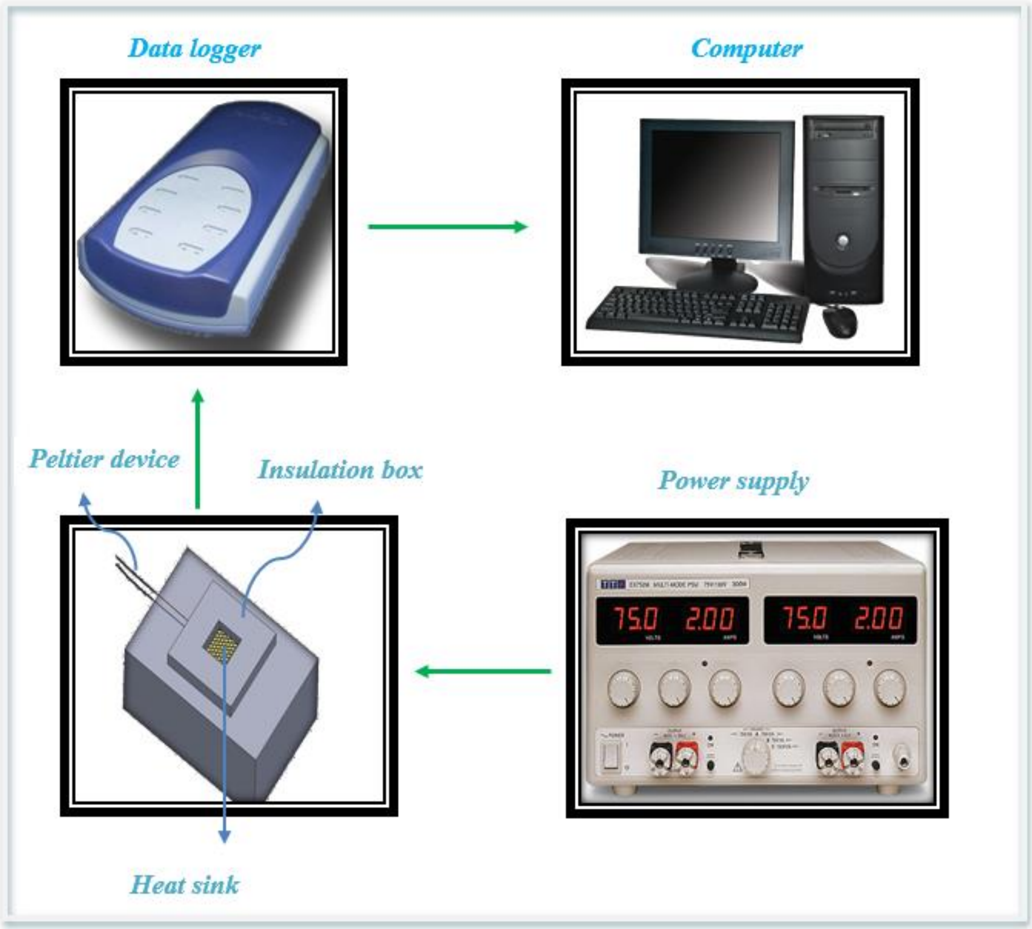


Fig 1.1: The schematic diagram of the experiment set up for a single peltier cooling device

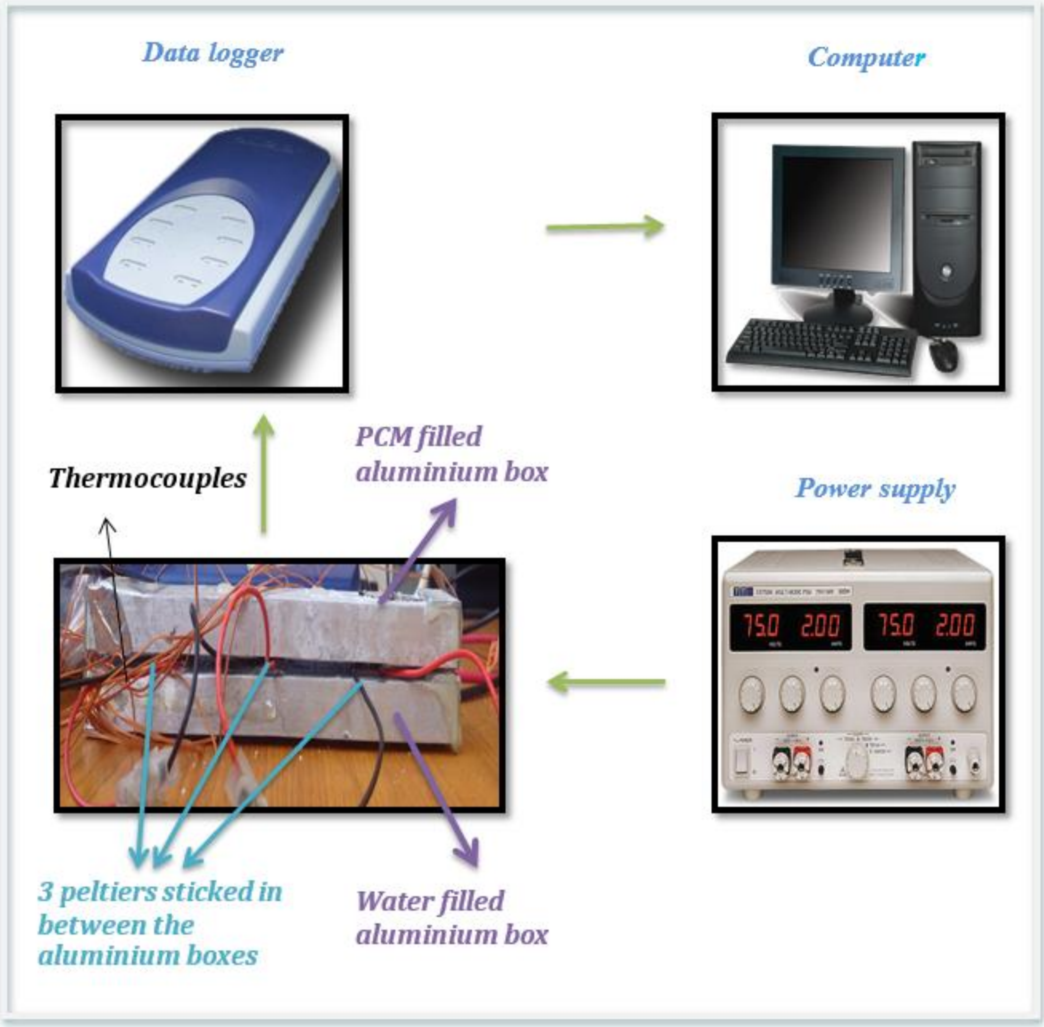


Fig 1.2: The schematic diagram of the experiment set up for three peltiers cooling device

Experiments were conducted using two different experimental setups to achieve the above objectives and two sets of experiments were conducted to study the peltier thermoelectric cooling performance using various heat sink configurations, different PCMs, various power levels, the amount of cooling and heating loads that can be achieved, coefficient of performance (COP) of peltier coolers and identifying the time and temperature changes in phase change material and water.

The main novelty of this work is the development of compact, light weigh active cooling device for MS patients that can be powered by batteries and operated easily with no moving parts or circulating fluids. Using phase change material allowed effective operation of the device without the need for mechanical fans”.

1.3 Thesis outline

This thesis consists of four chapters. Chapter one introduces the research topic covered by this thesis. This section includes project aim, objectives and thesis outline.

Chapter two reviews research studies on multiple sclerosis (MS), cooling technologies and phase change material. It also explains the basic principle of thermoelectric cooler (TEC).

Chapter three presents experiments carried out using single peltier test facility, different heat sinks (HSUs) and phase change material (PCM) to investigate the best performing HSU in terms of cooling and effect of using PCM with different power inputs of 0.5, 1, 1.5, 2, 3, 4, 5, 6 and 9 watts.

Chapter four presents experiments carried out with the three peltiers test facility using water filled aluminium box simulating the upper limb and phase change material filled box with two different PCMs to investigate the best performing one. Then COP, cooling and heating loads were calculated. At the end cyclic experiments were carried out in cycles of on and off processes to identify the time and temperature changes in phase change material and water and also to check the repeatability of the experimental results.

Chapter 2: *Literature Review*

2.1 Introduction

This chapter describes the background to the project. Section 2.2 includes description of Multiple Sclerosis disease, its definition, symptoms and methods of treatment. Section 2.3 describes various cooling technologies with particular focus on peltier cooling devices, while section 2.4 describes phase change material and their use for heat storage.

2.2 Multiple Sclerosis

2.2.1 Definition

Multiple sclerosis is an inflammatory autoimmune disease of the brain and spinal cord (Central Nervous System: CNS), which controls the activities and movements of a person [1]. MS affects 2.5 million people around the world and mainly females [2]. This disease may happen at any age however; most People with MS are young adults between the ages of 20 to 45 years old and about three times as many women as men have MS [3,4]. MS is much less common in Native American, Inuit, African and Asian populations [3,5]. From beginning of symptoms the average survival time is 30 years; MS patients life is 5 to 10 years shorter than those without the sickness [3]. Researches show that first-degree relatives of MS patients are at a higher risk of having the illness by seven times more than the general population [3].

Myelin is a substance that covers and protects the nerve fibers. In MS, the immune system attacks myelin in the central nervous system that leads to the creation of scar tissue or sclerosis and causes communication problems between the brain and the rest of the body. Ultimately, the disorder can cause the nerves to degenerate or become damaged forever [6,7].

For the pathologist, Multiple sclerosis is an illness of the CNS, exhibiting as severe inflammatory axonal loss and demyelination with limited remyelination, concluding in the chronic sclerotic plaques from which the sickness name comes. For the neurologist, MS is a disease of young adults recognized according to paraclinical and clinical evidence for minimum two demyelinating lesions, affecting various parts within the brain or spinal cord at different times. For the clinical scientist, Multiple sclerosis is an inflammatory autoimmune disorder of the CNS in which information attained across a range of clinical and basic neuroscience disciplines have already permitted logical methods for treatment. For the patient, Multiple sclerosis manifests with unlimited variety of symptoms but with definite repetitive themes and an unpredictable development. For all these groups, multiple sclerosis stays a disorder that it’s solutions look achievable but are still elusive [3].

2.2.2 Symptoms

MS signs and symptoms are as follow:

- Sensory loss like paresthesias
- Heat intolerance
- Numbness
- Ataxia and tremor
- Muscle cramping and spasticity
- Bladder, bowel and sexual dysfunction
- Fatigue and dizziness
- Blurred vision
- Pain
- Impairment of speech
- Subjective cognitive difficulties regarding concentration, attention span, judgment and memory
- Depression
- Weakness
- Irregular twitching of facial muscles and facial weakness [8]

2.2.3 Diagnosis

MS is recognized based on clinical findings and supporting evidences from tests, which involve the followings:

- Magnetic resonance imaging (MRI): for confirming Multiple sclerosis and controlling development of the disorder in the central nervous system

- Lumbar puncture: it is beneficial if MRI is inaccessible or MRI results are not distinguishable
- Evoked potentials: for diagnosing subclinical lesions, however its outcomes are not precise for MS [8]

2.2.4 Classification

MS is classified based on clinical criteria, containing time to illness development, repetitiveness of clinical relapses and lesion progression on MRI [8-12]. Four main MS categories are as follow:

- **Relapsing-remitting MS (RRMS):**

This is the most common form of MS with around 85% of cases primarily diagnosed with it [13]. It is identified by exacerbations (relapses) and then remission episodes (periods of partial or complete recovery). In remission period, the signs either get better or go away [13]. These flare-ups are attacks of deteriorating neurological function [7, 14]. Two subcategories that sometimes are included in RRMS are as follow:

- Benign MS: MS with nearly an entire remission between relapses
- Clinically isolated syndrome (CIS): It includes only one phase of neurologic signs [8]

- **Secondary progressive MS (SPMS):**

This type of the disorder follows a primary phase of relapsing-remitting MS. After this initial period, the illness starts to get worse, with or without episodes of remission [14]. The time to switch from relapsing-remitting MS differs from one person to another, but usual time span is 20 to 25 years after diagnosis of MS and initial manifesting [13]. There is no evidence concerning the percentage of patients who will progress to this course of the disorder, since this presentation of the sickness is not primarily diagnosed [7].

- **Primary progressive MS (PPMS):**

In this type from the beginning of MS, neurological function gets worse with no remission phase [13]. It is most common in patients who are older than 50 years at start of the disease and around 10% of individuals are primarily diagnosed with this form of MS [13]. The rate of the disorder development differs from one to one and this MS type is more resistant to the medications [13, 14].

- **Progressive-relapsing MS (PRMS):**

5% of patients are initially diagnosed with this course and this is the most rare type of MS [14]. This type is known by being progressive from the onset of the disease with exacerbations [13]. Because of the exacerbations that do not exist in primary progressive MS, progressive-relapsing MS is different from PPMS. Courses may differ from one to one, as no two patients will have precisely the same experience from their MS courses [14]. Figure 2.1 shows a visual demonstration of various MS courses.

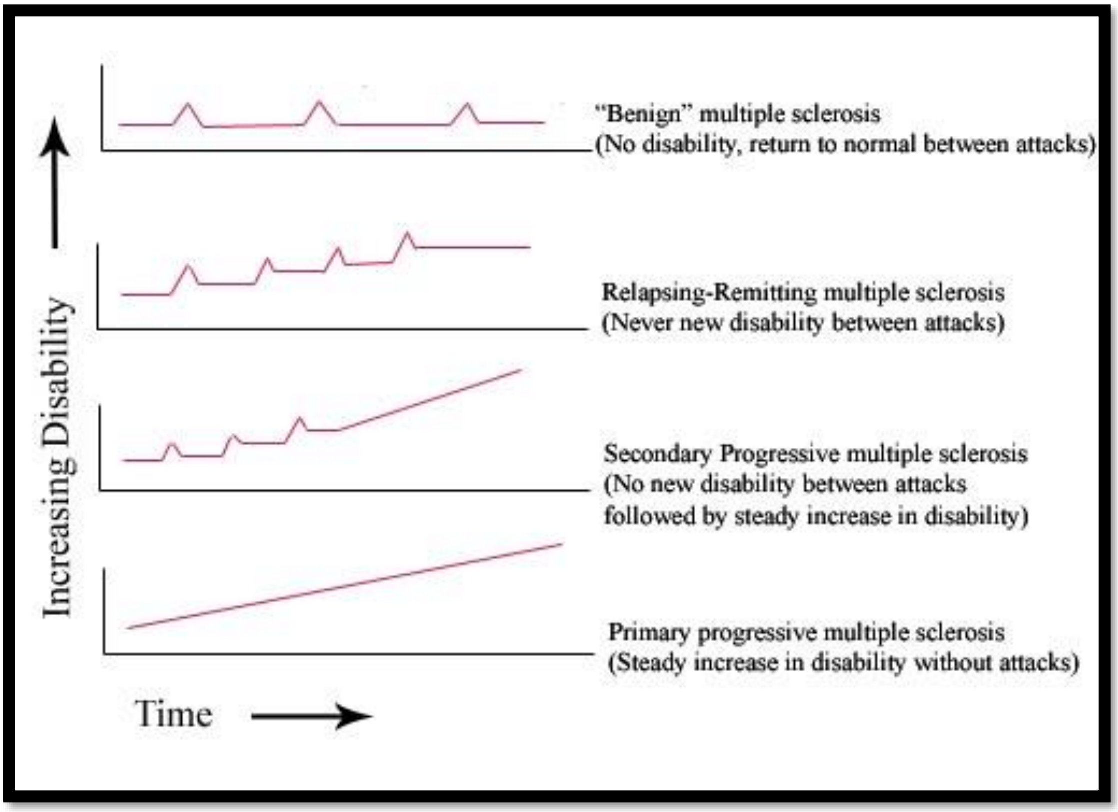


Fig 2.1. Different courses of MS [15]

2.2.5 Treatment

MS treatment is broken down into 3 divisions, which involve **disease modifying**, **symptomatic** and acute **attacks** [16]. Disease modifying therapy focuses on management of the disorder in long term with the goal to slow cognitive decline and disability progression, decrease relapse rates and reduce severity [16]. Treatment is extremely variable and differs from patient to patient based on side effect profiles, preference of prescriber, disease severity and cost. Disease-Modifying Agents for MS (DMAMS) that are approved by the US Food and Drug Administration (FDA), can decrease disorder progression in patients who have relapsing forms of MS [13].

Symptomatic therapy helps to keep life quality of a patient that can be hard, as drugs therapy don't have promising results for many of MS symptoms. Symptoms like fatigue, **tremor**, bowel and bladder symptoms, sexual dysfunction and spasticity will most likely improve by pharmacologic management and as the signs appear should be initiated. Spasms and pain usually improve with baclofen whereas bladder urgency and frequency typically respond to oxybutynin [20]. Around half of MS patients will get depressed, so it is important to seek treatment and counselling and also be aware of mood changes [21]. One of the methods that helps with **decreasing** the **tremor** intensity is **extracting heat** from the entire body [21].

Acute attacks treatment is focused on the exacerbations treatment, which affects functional ability of a patient. Acute relapse therapies are as follow [8]:

- Plasmapheresis (Plasma exchange) can be used temporarily for serious attacks if steroids are useless [22].
- Dexamethasone is usually effective for acute disseminated encephalitis and severe transverse myelitis.
- Methylprednisolone (Solu-Medrol) can speed up improvement and recovery from a serious exacerbation of MS.

2.2.6 Improving MS by extracting heat from the body

There is "pseudiexacerbation" in about 80% of MS patients, which is heat intolerance and causes a symptom exacerbation for the patient because of heat exposure and doing exercise or both. Though, when the body temperature goes back to the average temperature the patient will recover from the symptoms without any damages to the body. The symptoms include decrease in cognitive function, weakness, extreme numbness, blurred vision, tremor and fatigue. The heat intolerance varies in type of symptoms and severity, threshold and in terms of time length to resolve symptoms.

When the demyelination happens, the nerves ability to function will reduce and heat will decrease the impulse transmission of nerves. So, even if patient's body temperature increases slightly, it would be enough to cause the heat intolerance symptoms. Because of that for many years the "hot bath" test was used to diagnose MS, as most of the people are sensitive to heat. An individual suspected of having multiple sclerosis was inserted in a water hot tub and if the neurologic symptoms were appeared or worsened, it was evident that the person had MS. Patients with heat sensitivity and quicker symptoms progression are responsive to extracting heat from their bodies and their symptoms will vanish fast as well [24].

Thus, cooling down the body would decrease the heat intolerance and hence the physical performance of the MS patients could be developed. By extracting heat from the body, many MS patients experience alleviation from the unwanted signs. It is initiated by a mixture of decrease in activity of muscle spindle, varied muscle properties and nerve conduction velocity [23].

➢ Why cooling down via forearm?

Specialized subcutaneous vascular structures [arteriovenous anastomoses (AVAs) and associated retia venosa] underlie the soles of feet, the palms of the hands, the ears and face (the non-hairy skin surfaces of the human body) [23]. It delivers a large blood volume through the whole body and the blood flow can be equal to 60% of the cardiac output, which is as high as 8 l/min. To get rid of the excessive heat from the whole body the blood circulation through the specialized vascular structures is vital. This would have a main effect on the body core temperature, particularly on organs and active muscles that are receiving high percentage of the cardiac output.

For optimizing heat exchange throughout the retia venosa underlying the non- hairy skin surfaces of the hands and feet a portable cooling device was used by Feys et al [25]. In the device an airtight chamber surrounds a foot or hand and to increase the rete venosum of the enclosed appendage a pressure differential is used. It causes to draw a boosted blood volume thus improving the cooling rate. Based on clinical trials, cooling the forearm outer skin down to 18°C for period of 15 minutes can reduce tremor.

Clinical trials also showed that tremor reduction continued throughout 30-minute post cooling evaluation phase [25].

Reducing the body core temperature deliberately to a range of about 32° to 34°C is called therapeutic hypothermia or targeted temperature management. M.Hozler studied various devices for fast induction of hypothermia. The studied methods are as follow:

I. Surface cooling devices, which are non-invasive, and range from simple ice packs to sophisticated machines with automatic feedback control.
II. Drugs and cold liquid ventilation as other non-invasive methods.
III. Invasive cooling methods include the administration of ice-cold fluids intravenously, intravascular cooling catheters, body cavity lavage and extra-corporeal circuits, which are still in experimental stage.

The best technique and timing for the induction of hypothermia have not yet been determined, and now it is a main topic of ongoing research. The induction of hypothermia needs to be a vital element of the preliminary assessment and stabilization of the patient [26].

2.3 Cooling technologies

The technique of forearm cooling for intention tremor in Multiple Sclerosis has been investigated in 2005 by **P Feys *et al.*** Relevant researchers like **Dennis A Grahn *et al.*** updated the hand cooling method in 2008 and during the period many positive outcomes achieved. So, for further investigation on this MS treatment method the results found by previous researchers could be used as reference.

P Feys *et al.* investigated the effects of peripheral cooling on intention tremor in Multiple Sclerosis. In this study, eight men and ten women (Total 18) with the average age of 44.5 years, ranged from 18 to 63 years old who were diagnosed with MS, were selected to run the test. Deep (18°C) and moderate (25°C) cooling was done for 15 to 23 minutes and the skin temperature reduced at the elbow by 13.5°C and 7°C, respectively. Afterwards to discover the difference in total tremor amplitude and frequency tests like wrist step tracking and finger tapping were done before and up to 30 minutes after the cooling process. As an outcome of the study, a huge decrease in tremor amplitude was shown after the cooling process. However, the main factors that initiated the decrease were not completely known, thus more studies need to be done to solve the unexplained issues [25].

Dennis A Grahn *et al.* investigated the effects of extracting heat from the palmar surfaces of the hand on MS patients would be beneficial on reducing heat in their bodies. In this experiment, for the heat extraction process a chamber with an elastic sleeve was used and one hand was inserted into it. Afterwards, temperature was maintained at 18 to 22°C and pressure was set to - 40 mm Hg sub atmospheric pressure while walking on the treadmill. In conclusion of this experiment, the results showed that extracting heat from non-hairy skin surfaces of the body of MS patients could allow increasing the duration of their physical activities. Though, the outcomes achieved here were only in the initial stage of the research [23].

Generally there are a number of cooling systems that are commercially available and are used for various applications. Also, there are cooling technologies that are currently under development through research work worldwide. The aim of this project is to develop an active cooling device that is lightweight, compact, easy to use and pause no risk to the user. Therefore this section will give an overview of the various cooling technologies and assess their suitability for this project.

2.3.1 Mechanical vapour compression Refrigeration (Conventional Refrigeration)

The most common cooling technique is with vapor-compression cycles as it is low in cost and easy to build a cooling device using this technique. Vapour- compression refrigeration has a heat engine that is running at the back; therefore heat is deposited in a hot reservoir by taking from a cold reservoir compartment [45]. The Mechanical vapour refrigeration is shown in figure 2.2.

2.3.2 Vapour absorption system

Vapour absorption system difference with the compression system is in using heat energy instead of mechanical energy to complete the refrigeration cycle. The heat energy may be obtained from an electric heater or a gas burner [47]. The absorption system utilises the affinity of one substance to the refrigerant to circulate the refrigerant in the cooling system and producing the cooling effect. Examples of such substances are water, which has affinity for ammonia refrigerant and lithium bromide solution, which has affinity for water refrigerant.

Figure 2.3 represents that heat is transferred from the refrigerated space to an evaporator, vaporizing the ammonia (refrigerant). The ammonia gas is absorbed into an ammonia-water solution and heat is transferred to water. Across a heat exchanger the solution is pumped to a generator. Ammonia boils off through a heater; the ammonia-water solution returns to the absorber. The ammonia gas loses heat to water in the condenser and returns to the evaporator as a liquid [48]. This cooling system is complex and requires the use of fluids and circulating pumps, thus there is potential of leakage in addition to risk in using moving parts. This system also requires relatively high temperature heat source, which pause significant risk to the user.

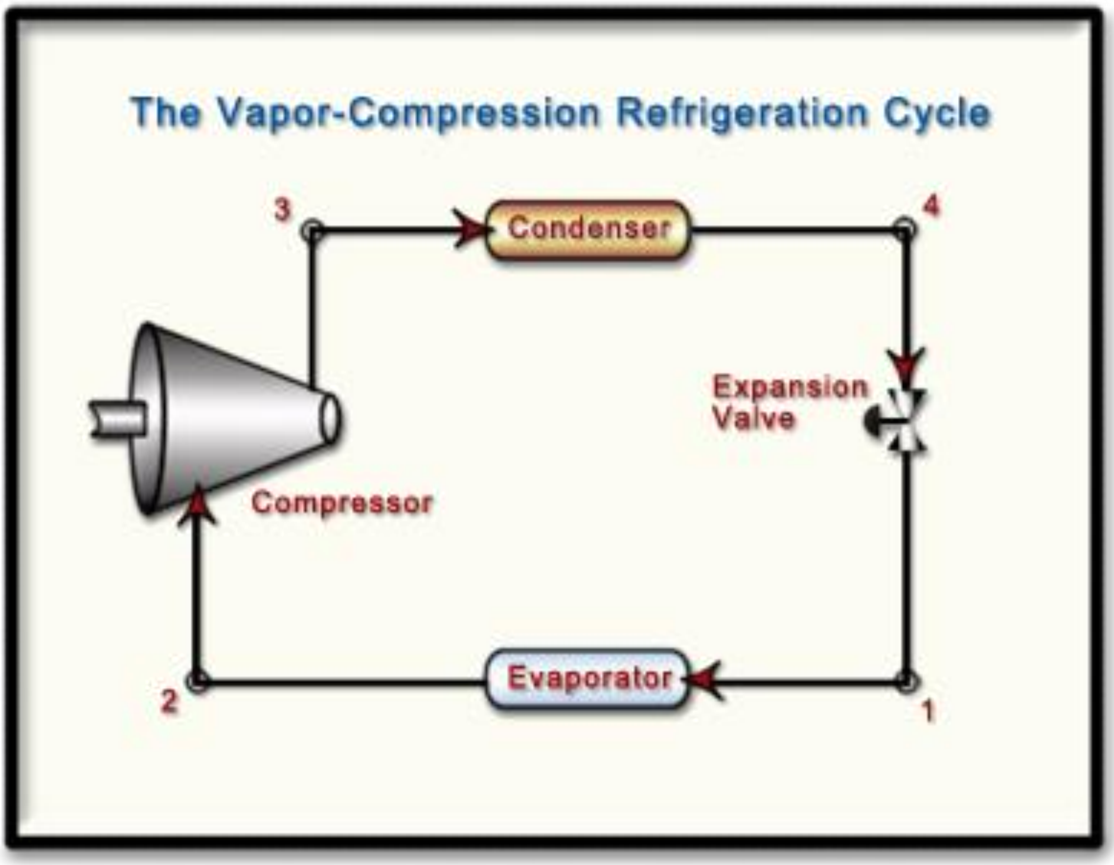


Fig 2.2. Mechanical Vapour Refrigeration [46]

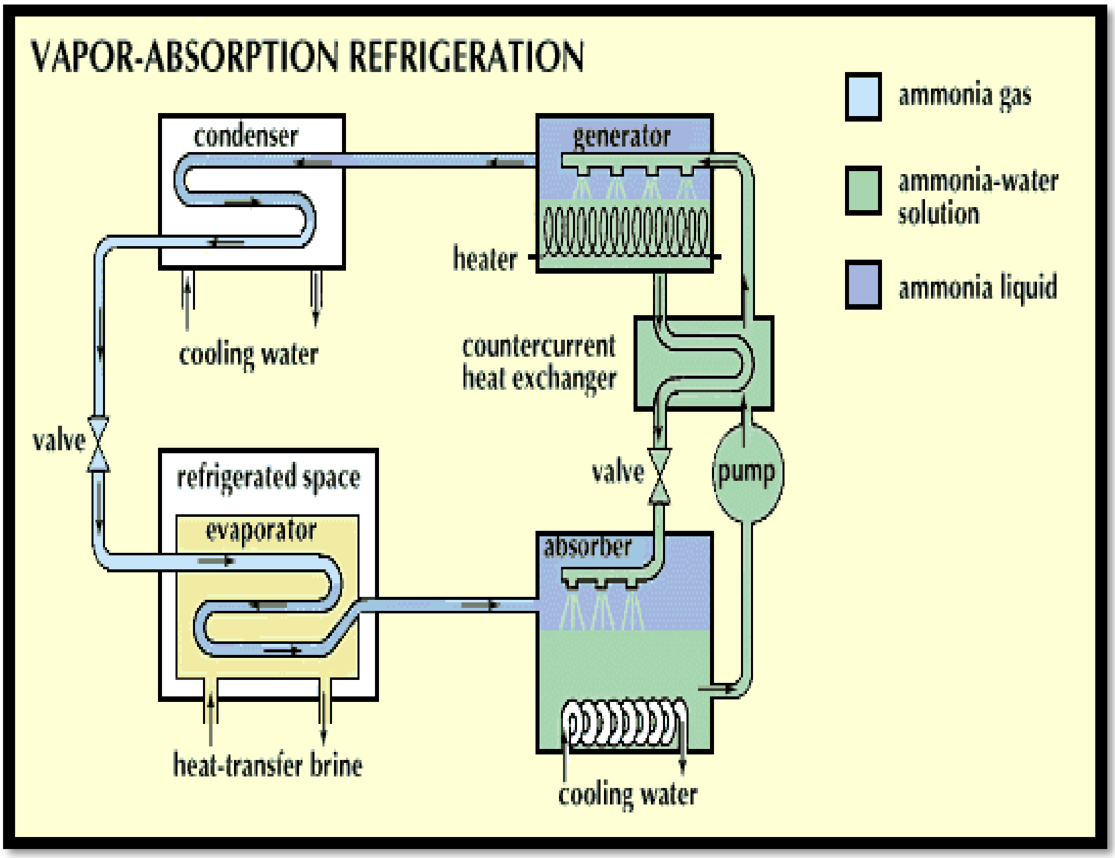


Fig 2.3. Vapour Absorption Refrigeration [48]

2.3.3 Magnetic refrigeration

Magnetic refrigeration is a cooling technology based on the Magnetocaloric Effect (MCE). When a Magnetocaloric Material (MCM) is exposed to a magnetic field, its temperature increases and as it is removed from the magnetic field it cools down, almost immediately. The effect is reversible. E.Warburg discovered the phenomenon, known as Magnetocaloric Effect (MCE) in 1881 [49]. The detailed Magnetocaloric principal is shown in figure 2.4 and the magnetic refrigeration cooling system is shown in figure 2.5. Magnetic refrigeration cooling system needs large magnets, which makes it non-portable and is still unavailable and under research [27].

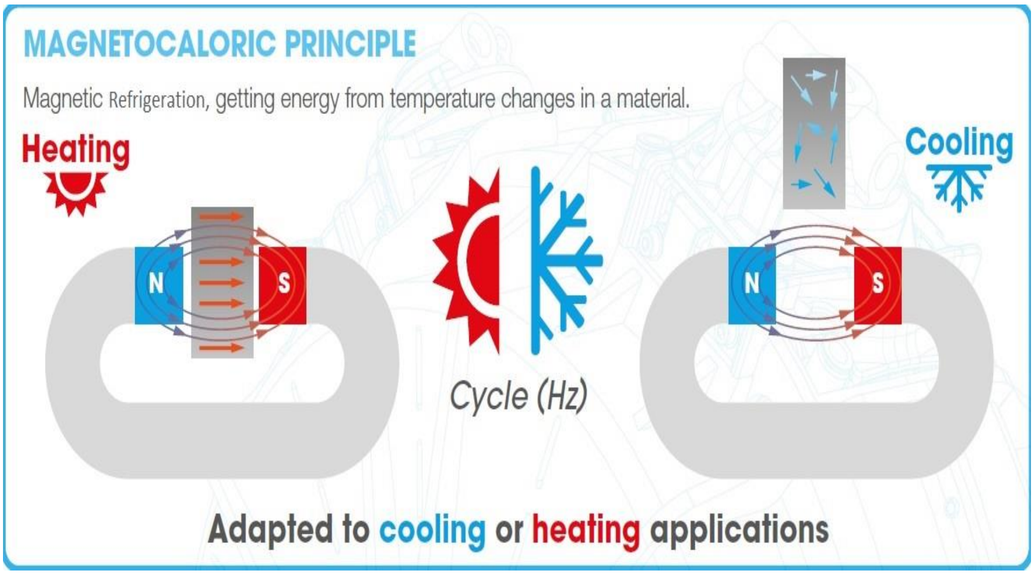


Fig 2.4. Magnetocaloric Principle [49]

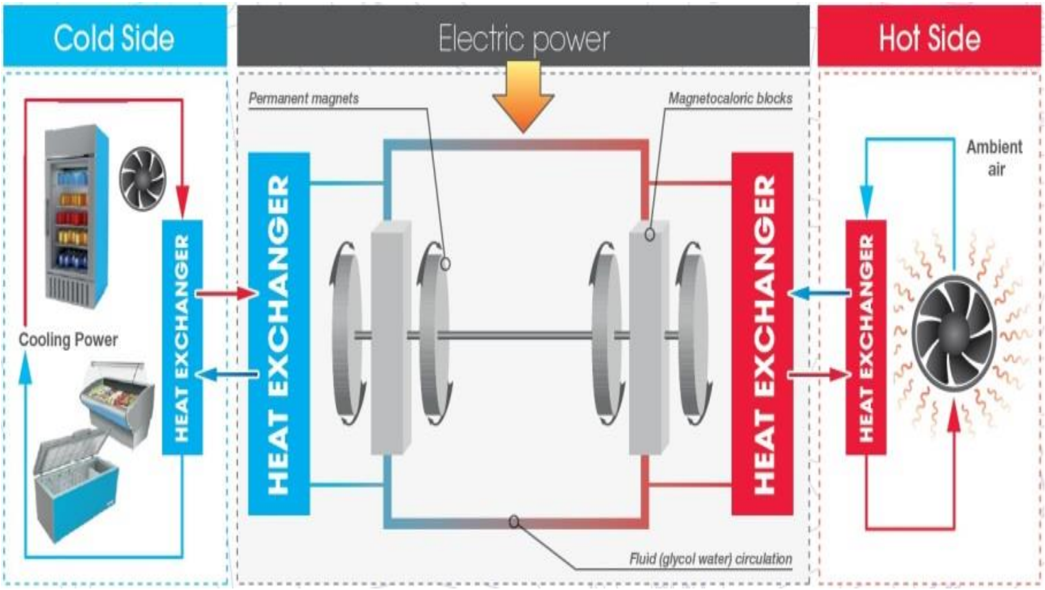


Fig 2.5. Magnetic refrigeration [50]

2.3.4 Thermoelectric or peltier device

Thermoelectric or peltier device uses Thermoelectric (TE) technology to provide a cooling effect. It also acts as a heater or heat pump, which transfers heat from cold to hot side, depending on the polarity of the applied voltage. The concept of TE technology is known as the peltier effect whereby, two different conductors absorb and release heat whenever there is current flowing through it. Peltiers includes an efficient TE conductor for refrigeration (an array of Bismuth Telluride) fixed between two ceramic plates. There are two types of Bismuth Telluride materials fabricated within the semiconductor array, which are N and P type. Heat moves in the direction of charge carrier flow [28]. Figure 2.6 shows the internal parts of the peltier plate.

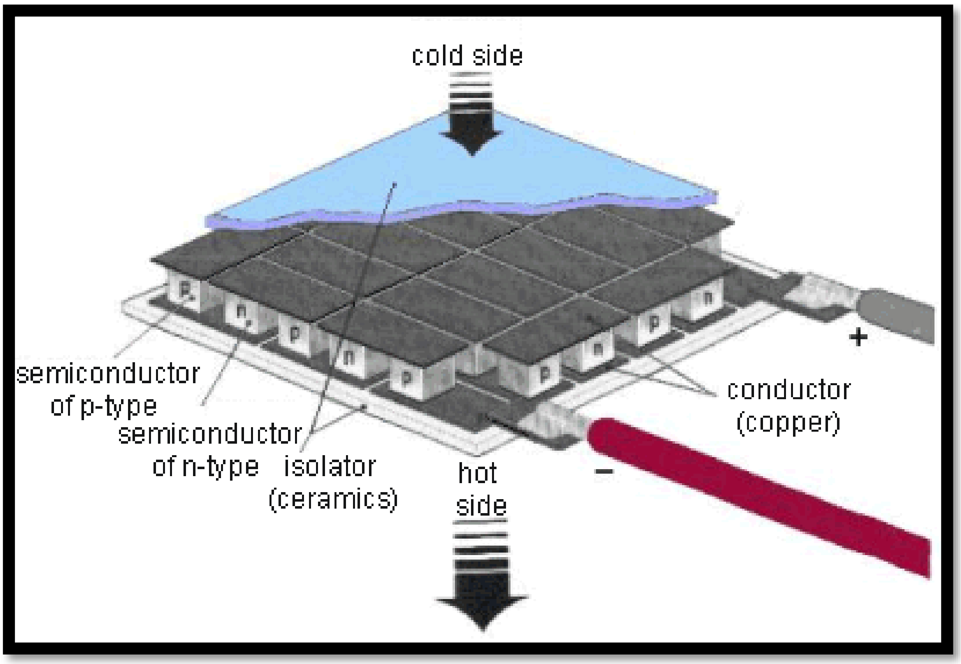


Fig 2.6. Internal parts of peltier plate [29]

Peltier or Thermoelectric coolers have been used to provide cooling in many applications including small domestic refrigerators, cooling electronic devices and cooling of human dead bodies. These coolers use the peltier or thermoelectric effect, which creates voltage when there is a temperature difference. Also when a voltage is applied to semiconductor material, it produces temperature difference contrariwise [28]. Peltiers are small in size, lightweight and do not have any moving parts so they don’t make noise, need less maintenance and are portable. They are low in cost and do not have any circulating fluid. As long as fixed voltage supplied, peltiers can produce steady cooling performances that can last long. Furthermore, increasing the temperature to normal levels can be performed by reversing the polarity of the applied voltage.

Amount of heat that is absorbed (q_a), the amount of heat that is emitted (q_e) and power can be described by equations (1), (2) and (3) [30]. The heat pumped is the sum of the heat conduction term ($\Delta T/\Theta m$), the Peltier effect term ($\alpha_m.T_a.I$), and the Joule effect term (I^2R_m).

$$q_a = \Delta T/\Theta m + \alpha_m.T_a.I - (I^2R_m/2) \qquad (1)$$

$$q_e = \Delta T/\Theta m + \alpha_m.T_e.I - (I^2R_m/2) \qquad (2)$$

$$P = V.I \qquad (3)$$

q_a is the amount of heat which is absorbed, Θm is the thermal resistance, α_m is the Seebeck-coefficient of the pn junction, T_a is the absolute temperature of the heat absorbed, R_m is the resistance of the module, T_e is the absolute temperature of the heat emitted and $\Delta T = T_e - T_a$. q_e is the amount of heat that is emitted. V and I are the voltage and the current from the power supply respectively.

Coefficient Of Performance (COP) describes the efficiency of the peltier cooler, which is shown by equation (4) [30].

$$COP = q_a/P \qquad (4)$$

Alaoui C. in 2011 had developed a model in Spice software to simulate the transient simulation of peltier cooling system and validated the model using experimental testing where a refrigeration chamber was designed and manufactured. The result is a good fit between the experimental data and simulation results. This model may help designer to have a better understanding and design on the Peltier modules [30].

2.3.5 Cooling devices used by MS patients

Different cooling devices were introduced to wear by MS patients during their normal daily life routines; but they proved to be power intensive, bulky and heavy [23, 25]. So the studies on this require to be continued to help with progress in Multiple Sclerosis medical treatment in the future. For example, ice water bath or ice pack is the most commonly used cooling technique. As the ice melts and loses its cooling capability, it can’t last long for the cooling application to cure MS patients.

2.4 Phase Change Materials (PCMs)

In cooling systems heat is pumped from low temperature thermal reservoir and rejected to a high temperature thermal reservoir such as ambient air or nearby water lakes using energy input. In a peltier cooling system, heat absorbed at the cold surface as well as the power applied have to be rejected at the hot surface to ensure effective and continuous operation. This heat rejection can be achieved using either passive or active techniques. Passive techniques include the use of various heat sinks as shown in figure 2.7. In such technology, heat is rejected using natural convection mechanism and no power is needed to operate the heat sink. Active heat rejection systems such as those shown in figure 2.8 require the circulation of a fluid (liquid or gas) in the heat sink. Passive heat rejection devices have a limitation on the amount of heat that can be rejected while active heat sinks have the disadvantage of using moving parts and potential of fluid leakage as well as the need to inputting power.

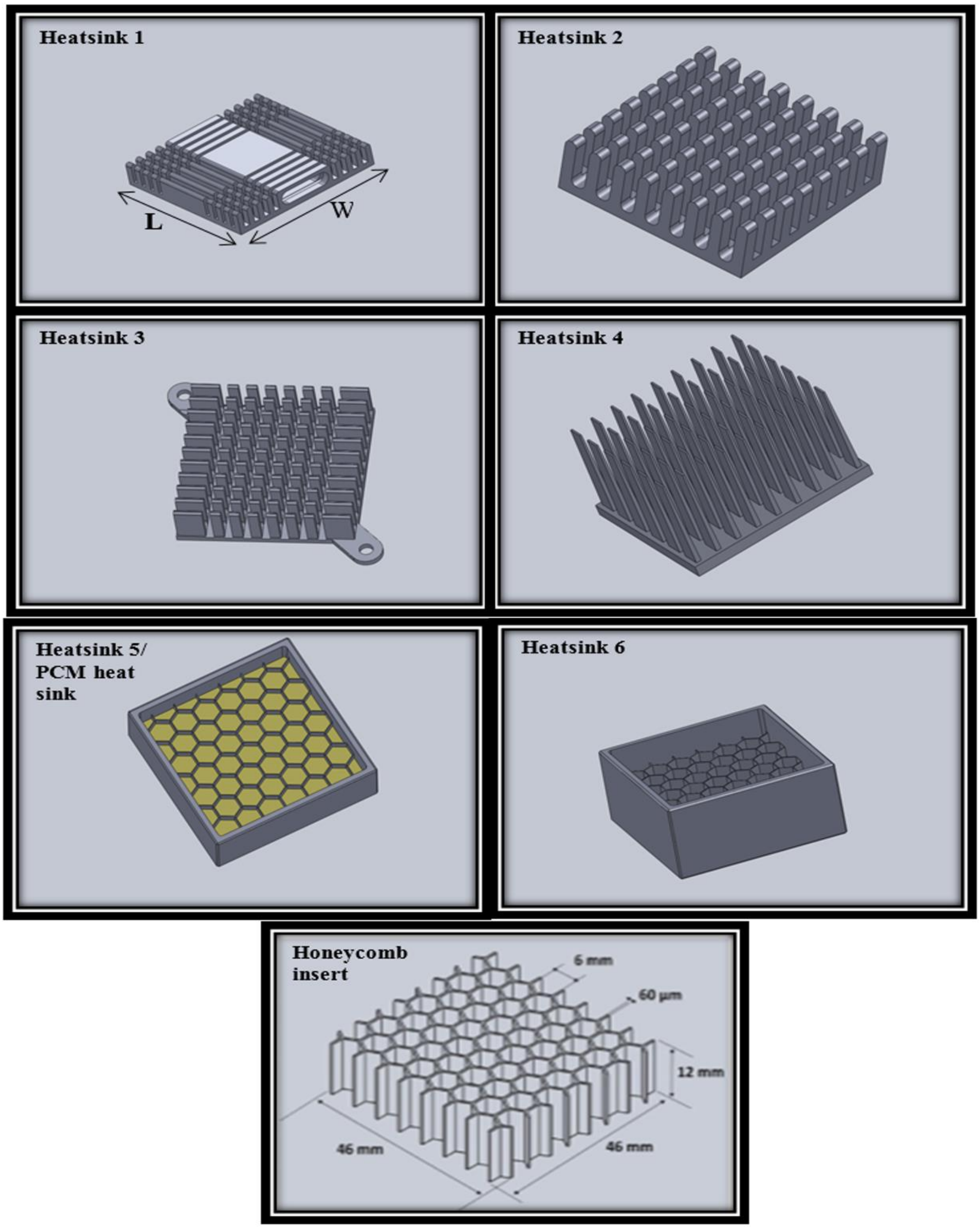


Fig 2.7. Various heat sinks & dimensions of honeycomb insert

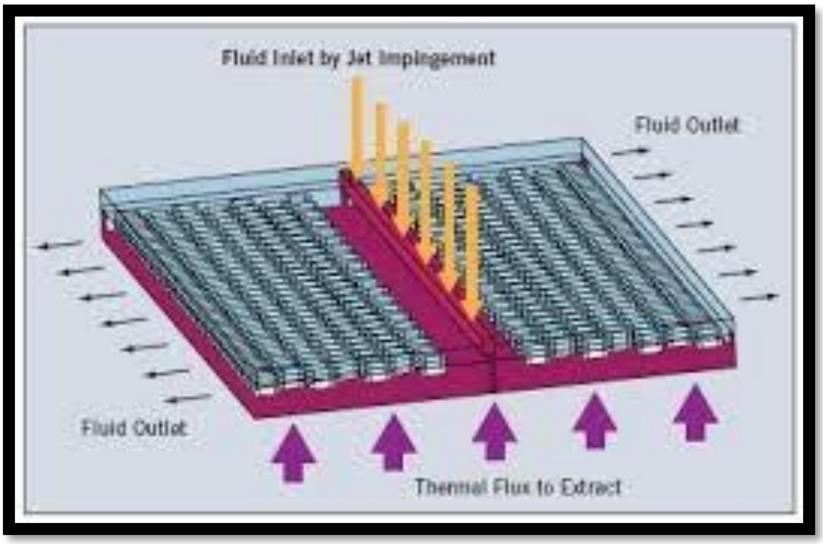


Fig 2.8. Heat sink with circulating fluid

Phase change materials (PCMs) can be integrated with passive heat sinks to enhance their performance as the amount of heat that can be absorbed during phase change processes (solid to liquid or liquid to gas) is significantly higher than that needed to increase the temperature of a fluid. PCMs were studied for various applications including solar application in buildings [35], cooling electronics [38-41], energy storage [42-44]. For cooling electronics **Kandasamy R et al.** used phase change material as based heat sink in transient cooling of electronics. The PCM had been tested in various heat sink designs and different power inputs. The results illustrated that by using PCM in heat sink cavities cooling performance will increase compared to when PCM was excluded [38].

The storage capacity of the latent heat storage system with a PCM medium is expressed by equations (7) and (8):

$$Q = \int_{T_i}^{T_m} mC_p\, dt + ma_m\, \Delta h_m + \int_{T_m}^{T_f} mC_p dt \qquad (7)$$

$$Q = m\, [c_{sp}(T_m - T_i) + a_m\, \Delta h_m + C_{lp}(T_f - T_m)] \qquad (8)$$

- **PCM classification:**

Three types of PCMs exist in any required temperature ranges that are organic, inorganic and eutectic. PCM categories are shown in figure 2.9.

Both organic and inorganic PCMs have been used during the experimental stage of this project in order to study their performances and choose the best one based on their thermal performances to be used for the cooling application.

Organic PCM benefits involves melting and freezing repetitively with no phase segregation and crystallization [35-38].

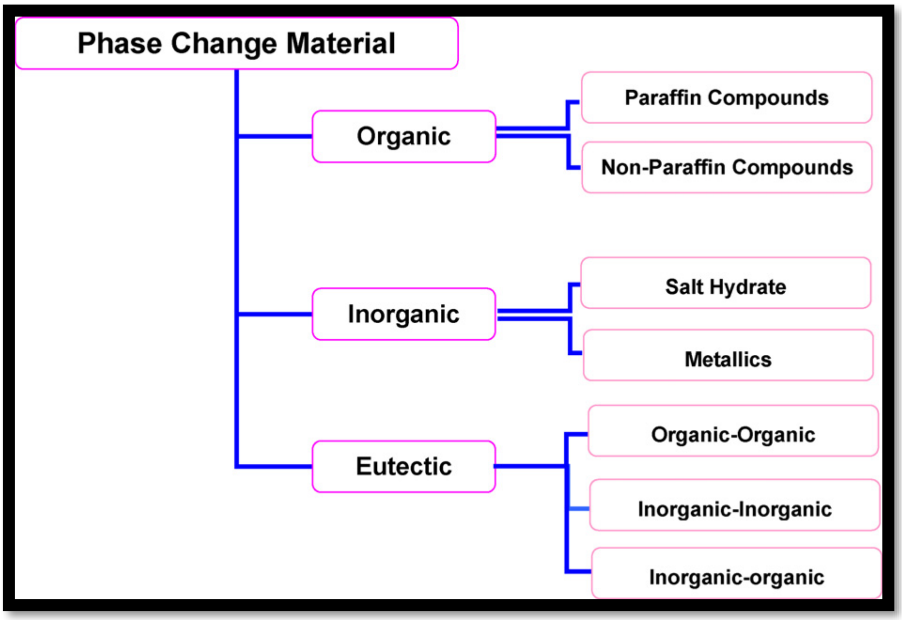


Fig 2.9. PCMs classification [35]

Nayak A. O et al. had run a test to compare between the CFD software analysis and experimental analysis of naphthalene, paraffin wax and sodium acetate tri-hydrate in thermal energy storage system. The results showed that Sodium acetate tri-hydrate had the most promising outcome in terms of storing heat energy between naphthalene and paraffin wax [43].

Arasu A.V et al. had done a research for simple paraffin wax and paraffin wax with nanoalumina (AL_2O_3) particles (nanoPCM) in a concentric double pipe heat exchanger and made a comparison between them. The outcomes showed that charge-discharge rates of thermal energy could be improved by using nanoPCM compared to simple

PCM. In conclusion, this study indicated that nanoPCM have higher potential to be used in different energy sectors [44].

2.5 Summary

The above literature review indicated that cooling can be used to alleviate the tremor symptoms of Multiple Sclerosis. Also, peltier cooling devices offer advantages in terms of being compact, light weight, has no moving parts and no fluids and are noiseless also they can be used for cooling as well as heating by reversing the polarity of voltage applied.

Finally, PCM materials like paraffin wax and OM37P can be used to absorb significant amount of heat like the heat rejected by the peltier devices.

Chapter 3: *Cooling Performance of Single Peltier With Various Heat Sinks*

3.1 Introduction

The first set of experiments that is explained in this chapter was performed using a single peltier to find the best heat sink (HSU), investigate the effect of using phase change material (PCM) and insulation.

3.2 Single peltier test facility

The single peltier test facility was developed to investigate the performance of a single peltier device, using different heat sink designs, power levels and Phase Change Material (PCM) in cooling application for designing a wearable cooling system. The test facility consists of the following items shown in figure 3.1:

- A power supply
- A single Peltier (Thermoelectric cooler/ TEC) device
- A heat sink to facilitate heat transfer from the Peltier device
- T type thermocouples, data logger and a computer
- A large and a small Insulating box

Figures 3.2 and 3.3 show the components and assembly of the insulating box-peltier setup. The large insulating box is made of polystyrene and has dimensions of 250mm length, 250mm width and 206mm height (see figure 3.2a). Polystyrene was used as an insulating material because of its low thermal conductivity, low cost and high availability. The small insulating box has an inner square hole with a 50mm length, 50mm width and 36mm height and it's outer square has a dimension of 147mm length, 147 mm width and 39mm height (see figure 3.2e). The big insulating box has been used for all of the initial set of experiments to insulate the set up and prevent excessive temperature changes but the small one has been used for PCM heat sink and HSU6 to investigate the insulation effect.

Aluminium peltier holder shown in figure 3.2b consists of two disks, upper one with a diameter of 38mm and the lower one with a diameter of 34mm. There is a cylinder between the surfaces that is also made from aluminium and has a diameter of 8mm and a height of 12mm. The peltier device has two square surfaces with dimensions of 13mm length, 13 mm width, 1 mm height and 2mm distance between the two surfaces as shown in figure 3.2c. The data logger is TC-08 with 8 channels to connect the thermocouples to it (see figure 3.1a).

To investigate the best performing heat sink, six different heat sink designs or heat storage units (HSU) were studied and named as heat sinks 1, 2, 3, 4, 5 and 6 (see figures 3.4a and 3.4b). Further details of the heat sinks and their figures are included in section 3.2.1. For each heat sink, four t-type thermocouples are placed to measure ambient, hot and cold side temperatures.

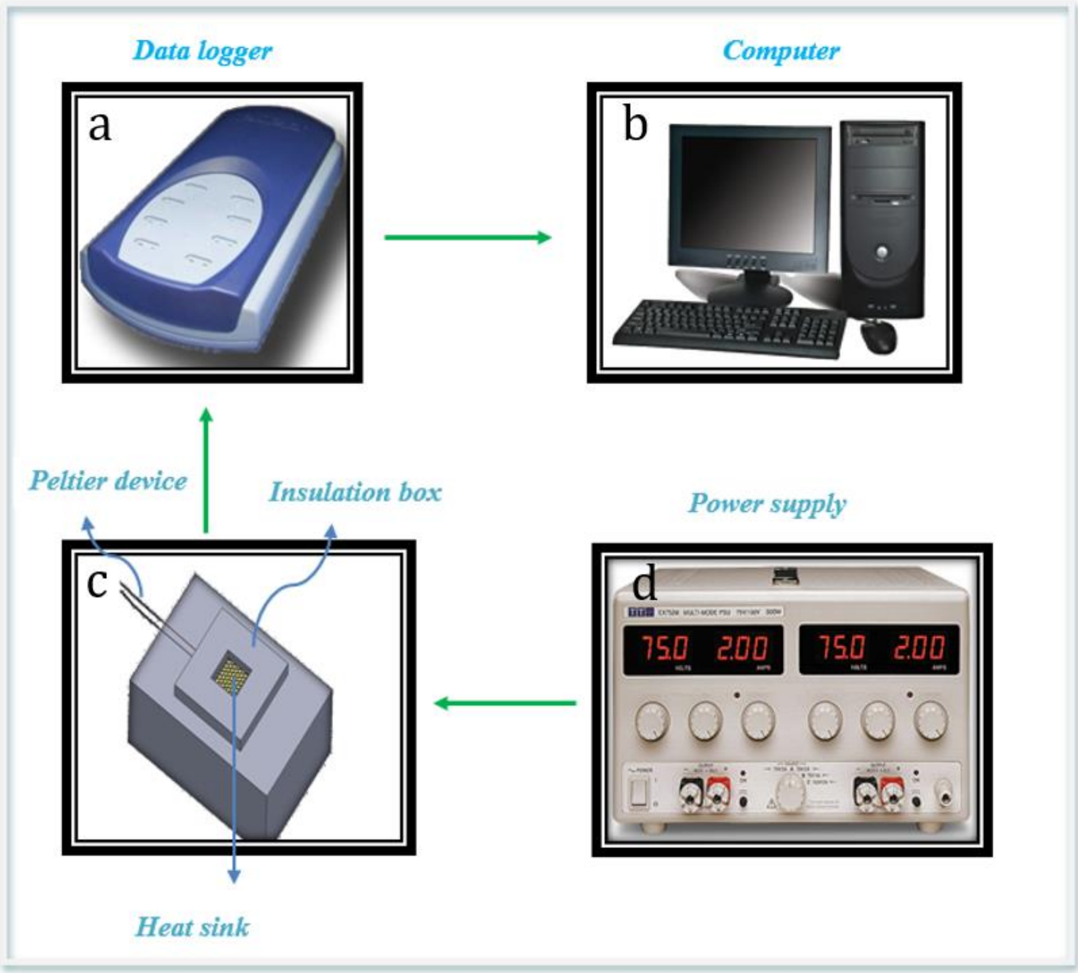


Fig 3.1. Experiment set up

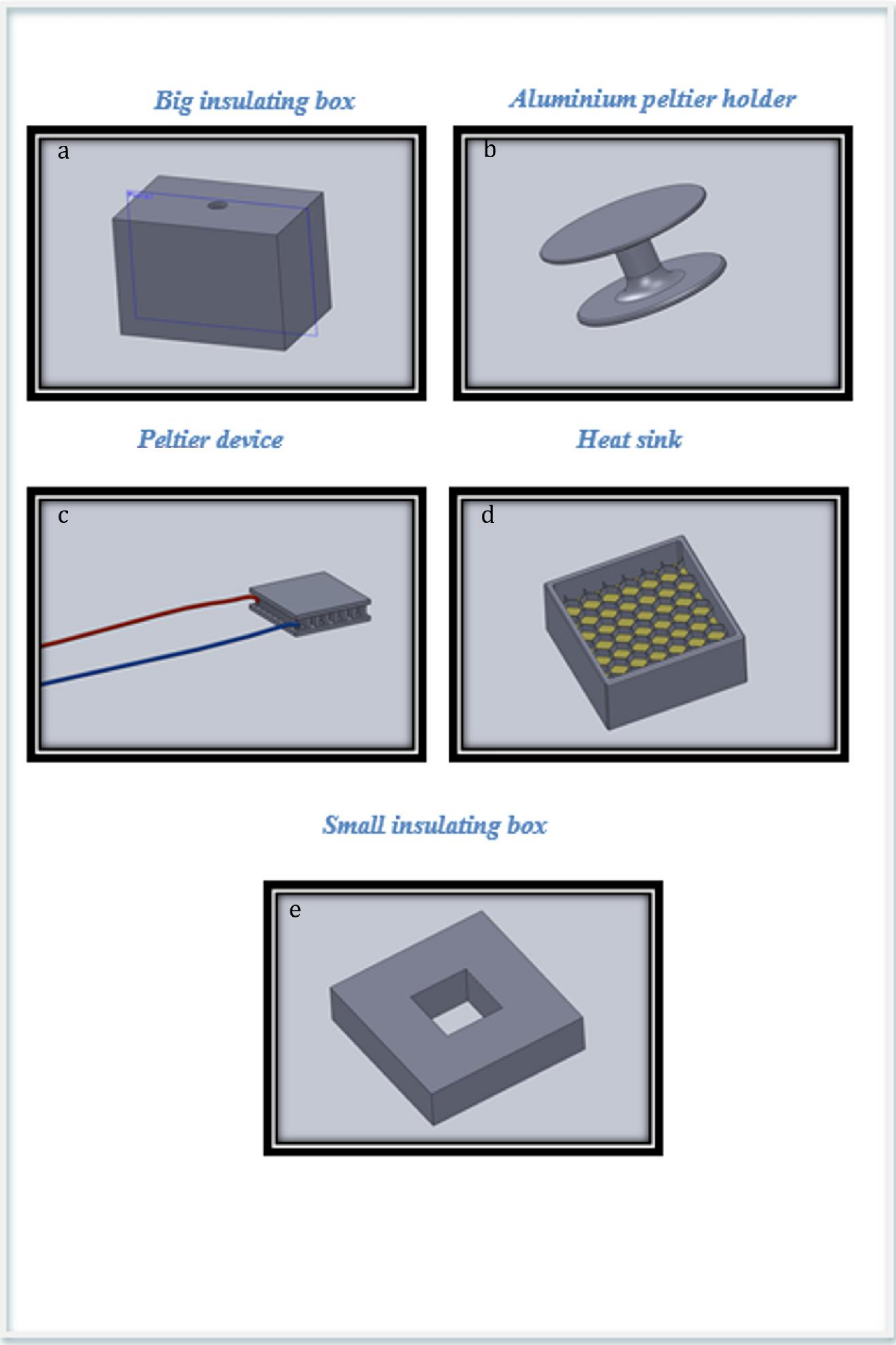


Fig 3.2. Different parts of the insulating box/ single peltier setup

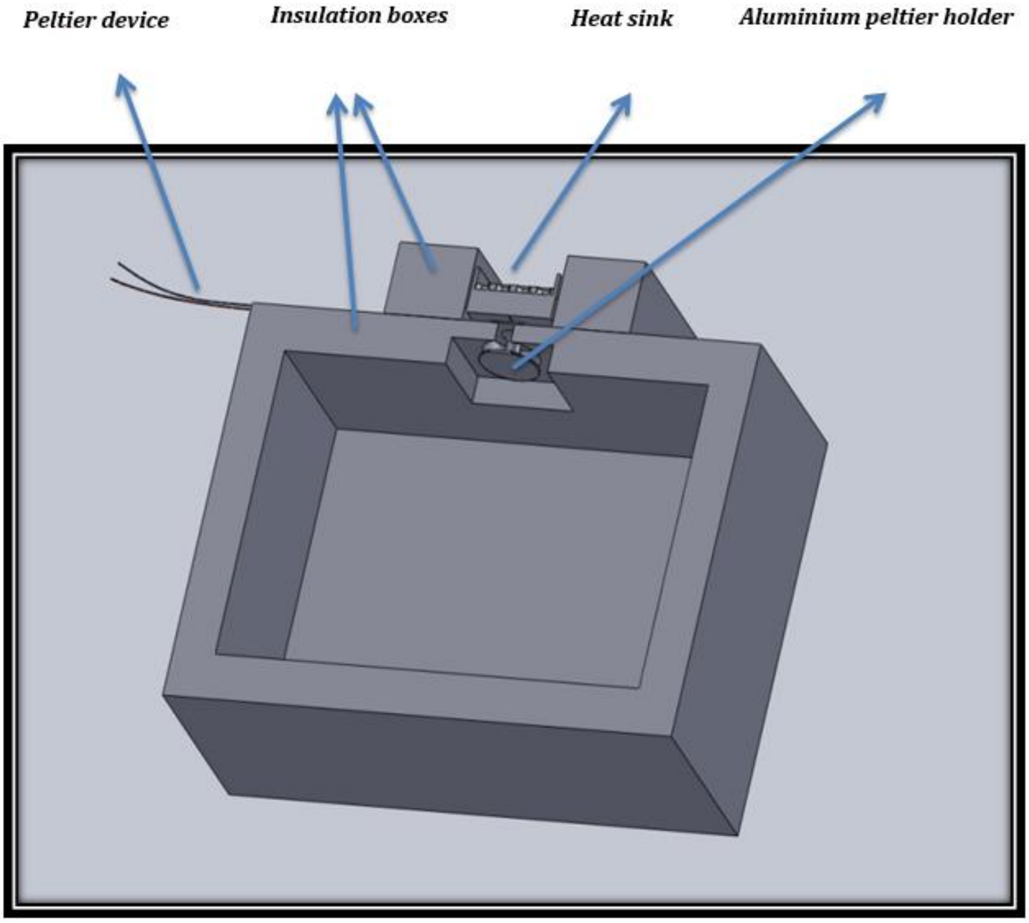


Fig 3.3. Side view of box inside

The peltier is a medium thermoelectric module with maximum power of 2.9 Watts and maximum current of 2.2 Amperes. The power supply is a Skytronic 650.682 adjustable dc power supply with maximum voltage supply equals to 30V and maximum current equals to 10A. The peltier specifications are shown in table 3.1 and the power supply unit specifications can be seen in table 3.2.

Table 3.1. Peltier/ thermoelectric specifications

Name of the peltier	Medium thermoelectric module
Delta T Max	74°C
Dimensions L x W x H	9 x 9 x 3.8mm
Maximum Current	2.2A
Maximum Power	2.9W
Maximum Temperature	85°C
Maximum Voltage	2.1V
Number of Couples N	8

Table 3.2. The variable power supply unit specifications

Name of the power supply	Skytronic variable
Reference number	650.682
Power input	240V AC – 50HZ
Output voltage	0-30 Volts DC variable
Output current	0-10 Amps variable
Max Ripple & Noise	<15 mV (at full load)
Dimensions	355×260×160mm
Weight	12 kg

Figure 3.3 shows the assembly of the insulating box-peltier test facility where the aluminium peltier holder is placed in the hole, which is on top of the insulation box with the cold part placed inside the box to prevent heat transfer from upper part. Also to minimise heat leakage from the hot side of the peltier to the cold side, a smaller insulation box is inserted around the peltier/ heat sink.

The top of the heat sink was left open to the ambient so that the heat sink will be exposed to the ambient air throughout the test and also to provide easy access for mounting probes and thermocouples.

The peltier device is stuck to the top aluminium circular surface and the heat sink is stuck on top of the peltier, both by using a thin holder layer of OMEGATHERM OT-201 thermal paste. Thermal paste or thermal grease will remove air pockets between peltier & heat sink and also between peltier & top aluminium circular surface to reduce contact resistance to heat transfer through these interfaces. It also increases thermal conductivity of the interface between the peltier and heat sink.

In the experiments, it is needed that lower peltier surface get cold and the upper one get hot so the red and black leads of the peltier should be connected to the respective positive and negative terminals of the DC power supply. Consequently heat will be pumped from the TE's cold side to the hot side and then to the heat sink.

3.2.1 Heat sinks and PCM used

For effective performance of the peltier, the heat absorbed on the cold side and the power input has to be rejected. The heat rejection mechanism has to be with least moving parts and compact to develop the portable cooling device so that it does not produce noise and requires less maintenance. To make the forearm cooling system lighter and portable heat sinks were used with the natural convection.

Six different heat sink designs or heat storage units (HSU) were tested and named as Heat sinks 1, 2, 3, 4, 5 and 6.

The heat sinks 1, 2, 3 and 4 designs are illustrated in figure 3.4 (a), heatsinks 5 and 6 designs are shown in figure 3.4 (b). The heat sink shown in figure 3.4 (b) called PCM HSU or HSU5 has a honeycomb insert and is filled with paraffin wax/ Rubitherm RT 42 PCM. Dimensions of honeycomb insert are shown in figure 3.4 (b).

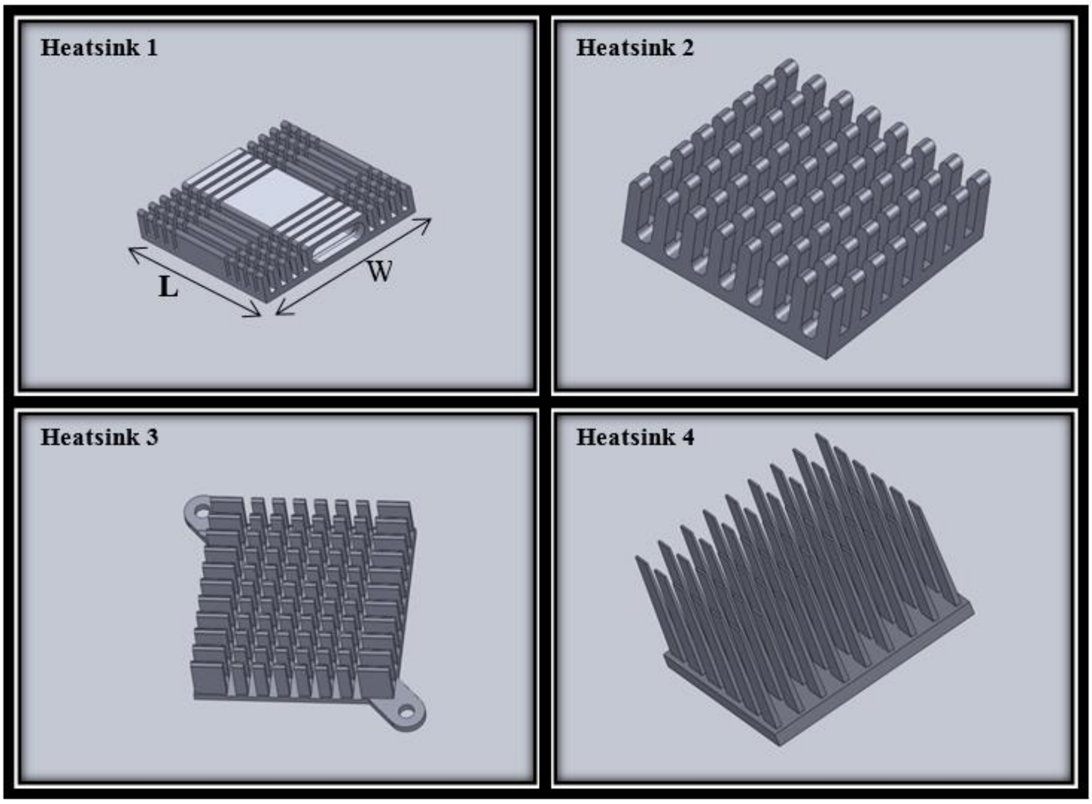


Fig 3.4. (a) Heat sinks 1, 2, 3 & 4 designs

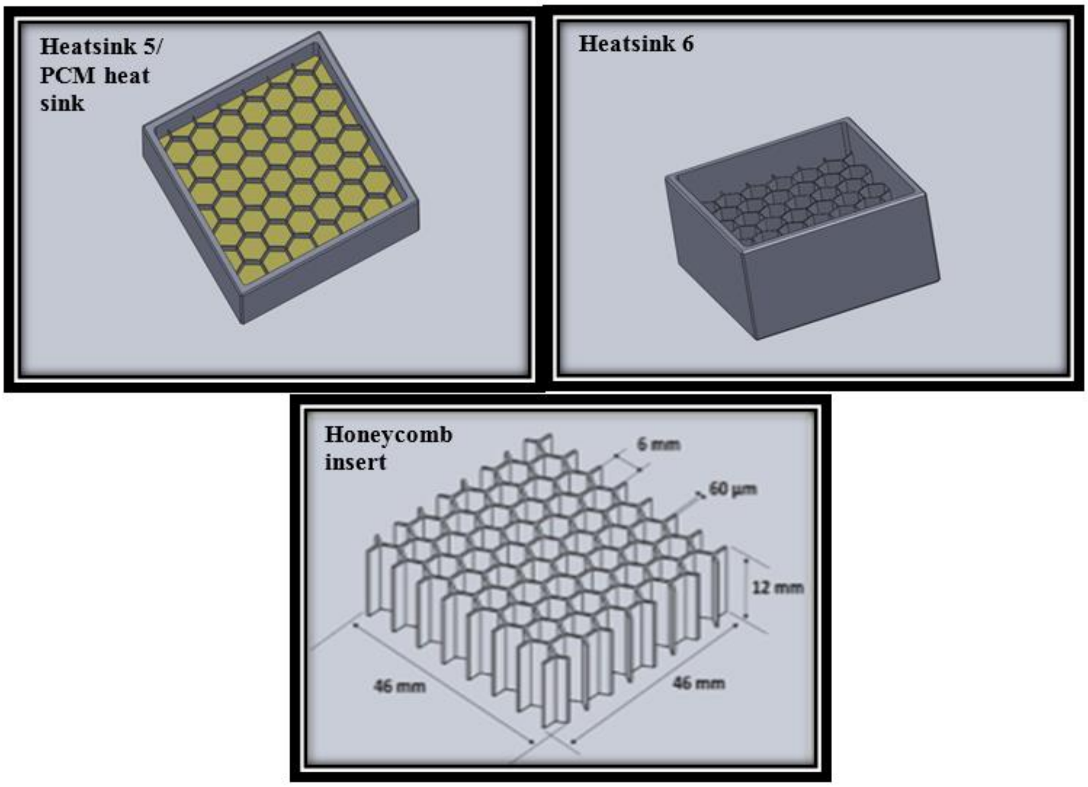


Fig 3.4. (b) Heat sinks 5 & 6 designs and dimensions of honeycomb insert

Heat sinks 1, 2, 3 and 4 were purchased and represent various heat sink designs used in computing systems. They are made of aluminium T6-6061. The aluminium was selected due to its ease of machining, high conductivity, relatively low density and low cost. PCM heat sink or HSU 5 has a honeycomb insert inside a single cavity and is filled with paraffin wax/ Rubitherm RT 42 PCM. Heat sink 6 has the same configuration and dimensions as PCM HSU 5 but it's not filled with the phase change material. The honeycomb insert is of hexagonal type and is made from extra hard 3003-alloy aluminium foil. It has a cell size of 6 mm and thickness of 60 µm as can be seen from figure 3.4 (b). The external dimensions of the various heat sinks are given in table 3.3.

Table 3.3. External dimensions of various heat sinks

Heat sink	Length	Width	Height
HSU 1	37 mm	37 mm	2.5 mm
HSU 2	27 mm	27 mm	6 mm
HSU 3	38 mm	38 mm	4 mm
HSU4	41 mm	38 mm	10 mm
HSU 5	50 mm	50 mm	25 mm
HSU 6	50 mm	50 mm	25 mm
Honeycomb insert	46 mm	46 mm	12 mm

Rubitherm RT 42 which is a paraffin and wax-based Phase Change Material with melting temperature of 42°C was the selected PCM due to the following reasons:

- Its melting temperature of 42°C is significantly higher than the ambient temperature that means no melting would happen at room temperature.
- Rubitherm RT 42 is a phase change material with high latent heat of melting of 174000 J/ kg and a commercially available PCM.

The paraffin wax PCM specifications are shown in table 3.4.

Table 3.4. Rubitherm RT-42 specifications

savEnrg™ PCM	Rubitherm RT-42
Phase Change Temperature (°C)	42
Phase Change Temperature (°F)	107
Density (Kg/m^3)	880
Latent Heat (KJ/Kg)	174

3.2.2 Measuring devices

3.2.2.1 Voltmeter

The peltier is driven by supplying DC power that was determined by measuring the input voltage and current. The current was measured by the power supply used while the voltage was measured using a voltmeter connected to the peltier directly.

3.2.2.2 Temperature sensors

For each heat sink, four t-type thermocouples are placed and named as follows to measure ambient, hot and cold side temperatures:

- Between the fins of the heat sink (hot side temperature), see Fig. 3.5.
- Under the top aluminium circular surface (cold side temperature), see Fig. 3.6.
- Under the lower aluminium circular surface (cold side temperature), see Fig. 3.6.
- Ambient temperature

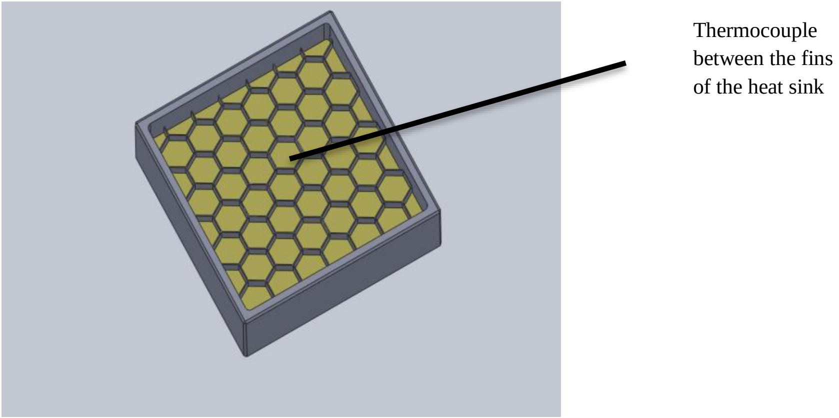


Fig 3.5. Thermocouple between the fins of the heat sink

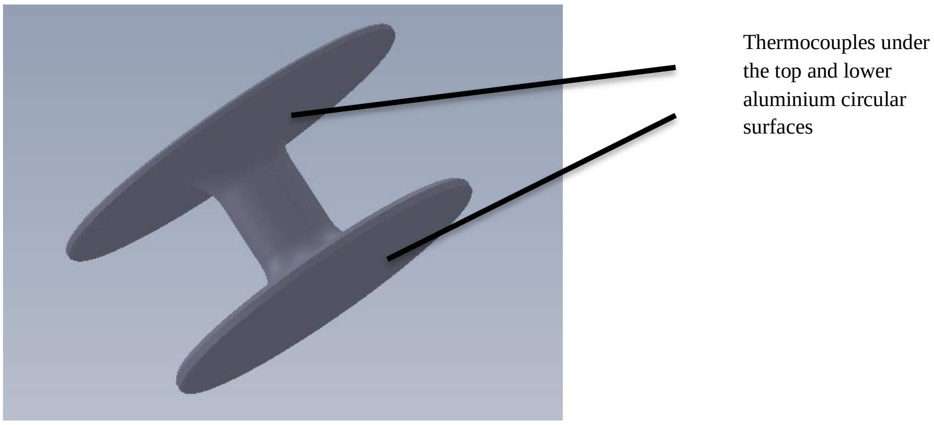


Fig 3.6. Thermocouples under the top and lower aluminium circular surfaces

Two thermocouples placed on the aluminium circular surfaces that were under the peltier to measure the cold sides temperature.

The mentioned thermocouples are connected to the channels of the data logger. The data logger is connected to the computer and the thermocouple temperatures are read by PicoLog software.

3.3 Results and Discussion

In this section the results of the experiment carried out to investigate the effect of heat sink designs, power levels and PCM on the thermal performance of the peltier device are presented.

The experiments can be divided into two series; the first series of the experiments were conducted using heat sinks 1, 2, 3 and 4 while the second series were performed using heat sinks 5 and 6.

In order to determine the best performing heat sink, the results were presented in terms of the cold temperature variation with time for different HSUs at various power inputs. The best heat sink was taken that can cool down to the desired temperature (18°C) and can maintain it for longer time. Also the temperatures of hot sides of the heat sinks were compared together, to prevent reaching excessively high values.

The temperature of heat sinks 1, 2, 3 and 4 were tested with power levels of 0.5, 1 and 1.5 Watts (W). Temperature distributions were measured and compared.

Then experiments were performed using heatsinks 5 and 6 to study the effect of PCM on thermal performance of peltier with power inputs of 1 W, 2 W and 3 W. In these experiments, liquid PCM was poured into the HSU5 and then the PCM were cooled to the ambient temperature. Afterwards, another experiment was carried out for heat sink 4 at power levels of 1 W, 2 W and 3 W and a comparison was made between HSU 4 and HSU 5 (PCM heat sink). The reason of doing the test only for HSU 4 among the first four heat sinks was due to its better performance in cooling application, which is explained in results and discussion section.

At the other step of the second series, the tests were done at constant power levels of 1W, 2W and 3W. As it can be seen in figure 3.4 (b), heat sinks 5 and 6 have the same designs except that HSU 5 has phase change material in it and HSU 6 does not have it and as PCM is able to absorb and release large amounts of energy so the powers for HSU 5 and 6 has been selected differently compared to the rest of heat sinks. In this case temperature distributions were recorded during melting process. The PCM volume was kept constant at 25mm by considering the volumetric expansion of the PCM when it melts. All temperatures were recorded and saved in the log file for more investigation and temperature versus time graph will be plotted in Microsoft Excel for comparison.

The duration of the first series of tests was 600 seconds (10 minutes) and for the second series it was 3600 Sec (60 minutes). Because PCM was used in the second series of experiments, therefore the duration was different from the first series.

3.3.1 Effect of different heat sink design configurations

Figures 3.7 to 3.9 compare the peltier cold and hot side temperatures using heat sinks 1,2, 3 and 4 at power inputs of 0.5, 1.0 and 1.5 watts respectively over a period of 600 seconds. Figure 3.5 illustrates the temperature variation with time of the cold and hot sides of the peltier using the heat sink designs 1, 2, 3 and 4 using power input of 0.5 W.

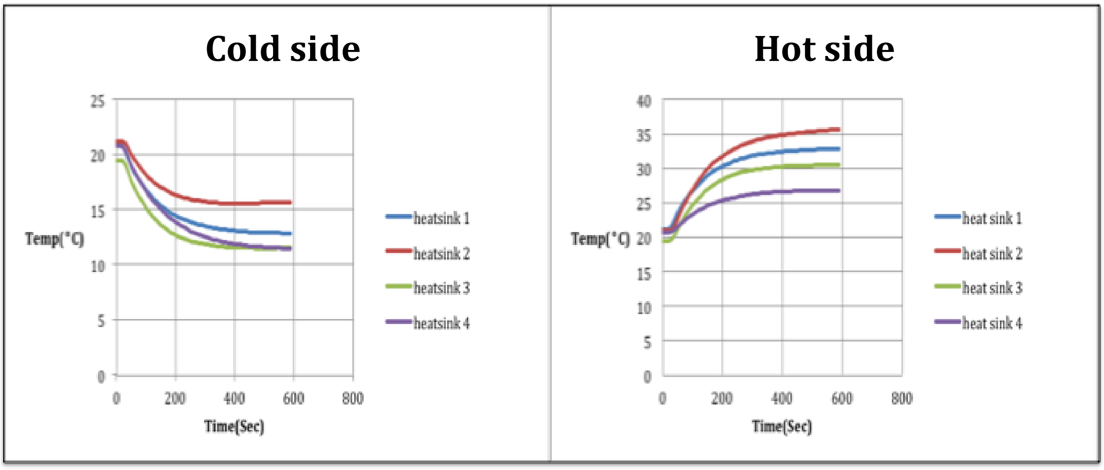


Fig 3.7. Temperature profile of heat sinks 1, 2, 3 and 4 during cooling and heating process at 0.5 W

It can be seen that the temperature variations for the four HSUs can be divided into two stages. In stage 1, the cold and hot temperatures change steeply with time due to the heat absorption by peltier device. In stage 2, both temperatures do not change significantly and start to stabilise. As shown in figures 3.7, heat sink 3 has achieved the coldest possible temperature which is about 11°C but it's hot side has a higher temperature (30°C) compared to heat sink 4 that is at 26°C.

Figure 3.8 compares the cold and hot side temperatures variation with time using the four different heat sinks using 1 W.

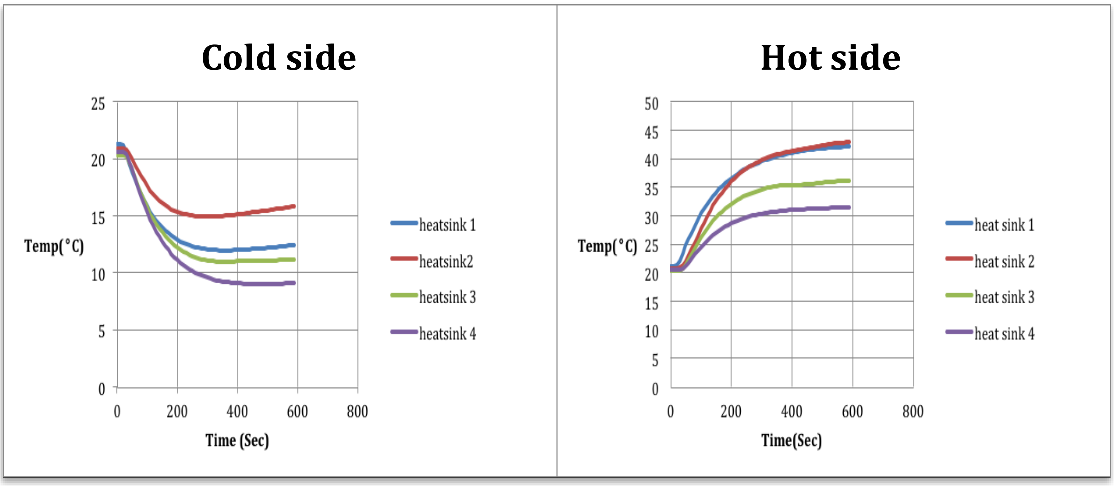


Fig 3.8. Temperature profile of heat sinks 1, 2, 3 and 4 during cooling and heating process at 1 W

As figures 3.8 illustrates, heat sink 4 has the lowest cold temperature at about 9°C after 6 min and also its hot side has a lower temperature compared to the other heat sinks. Its hot side temperature is approximately 31°C after 10 min.

Also the cold and hot temperatures obtained with application of 1.5 W presented in figure 3.9 shows that heat sink 4 has the lowest cold temperature of 8°C after 7 min and also its hot side has lower temperature compared to the other heat sinks which is 34°C after 10 min.

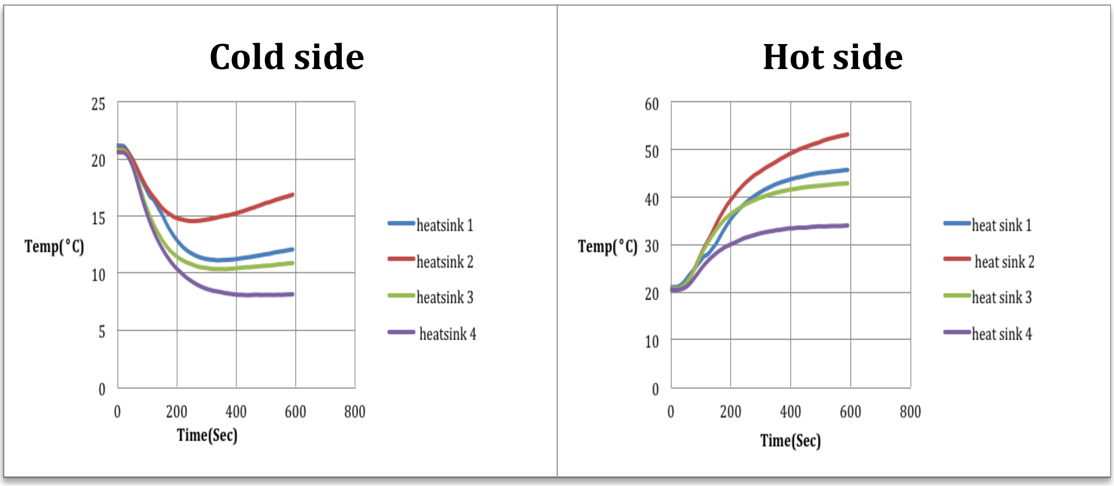


Fig 3.9. Temperature profile of heat sinks 1, 2, 3 and 4 during cooling and heating process at 1.5 W.

The results shown in figures 3.7 to 3.9 illustrate that heat sink 4 has the lowest cold temperature at about 9°C and also its hot side has the lowest temperature (34°C) compared to the other heat sinks. The results also indicate that, it can retain the temperatures for both cold and hot sides more stable, thus heat sink 4 was the best performing one based on thermal operation. As shown in figure 3.4a, heat sink 4 has high pin fins with effective heat dissipation mechanism.

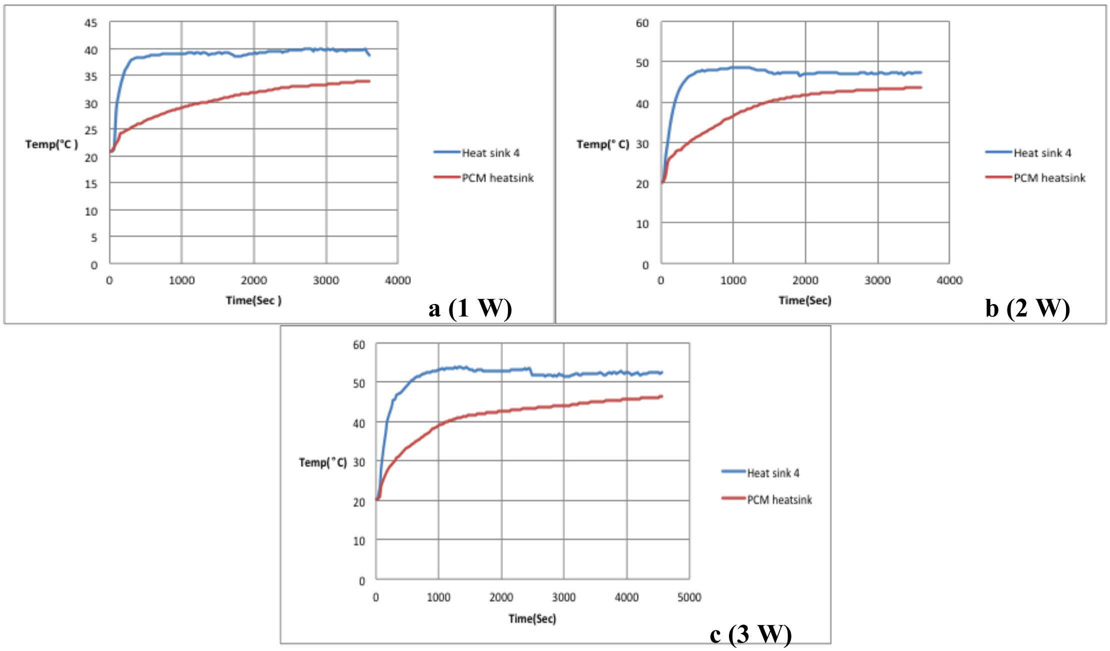
3.3.2 Effect of PCM

Figures 3.10 and 3.11 compare the temperature variation of heat sinks 4 and 5. Here the tests are conducted at higher power input and for longer time to ensure that low temperatures can be maintained for longer time. Figure 3.10 compares the peltier hot side temperature for both heat sink 4 and 5 at power input of 1W, 2Wand 3W over 3600 seconds. The ambient and the starting temperature is about 20°C for all the power inputs of 1, 2 and 3 Watts. As can be seen from figures 3.10 the temperature of the heat sink filled with PCM that is called PCM heat sink or HSU 5, is lower than the heat sink 4 that does not contain PCM. Heat sink 4 nearly gets its steady state after 200 seconds for different power levels of 1, 2 and 3W at the temperatures of 39°C, 47°C and 52°C respectively. While temperature of the PCM heat sink still increasing at a time of 200 seconds and is 6°C lower in average for the power levels of 1, 2 and 3W at a time of 60 min.

The performance of the PCM heat sink can be explained as follows. The melting temperature of the paraffin wax phase change material is 42°C and requires 174 kJ/kg for melting. Using 1 watt is not enough to melt the PCM during an hour and the highest reached temperature is 34°C as shown in figure 3.10 (a).

The temperature profile of the PCM heat sink using 2 and 3W shown in figures 3.10 (b) and (c) can be divided into two regions. In the first region, the temperature of the solid PCM increases with time to its melting temperature. The first stage took about 35 minutes to complete for 2 watts and 27 min using 3 watts. In the second region, as the PCM temperature reaches 42°C, it starts melting by absorbing the latent heat from the peltier hot surface. Although theoretically, the melting process should occur at constant temperature, practically this is hindered by the low thermal conductivity of the PCM. As the PCM layer in contact with the peltier hot surface heats up and starts melting, heat is transferred from this layer to the layer above through conduction thus the heat sink temperature continues to increase but at a lower rate to transfer the required heat for melting all the PCM material in the sink.

Hot side

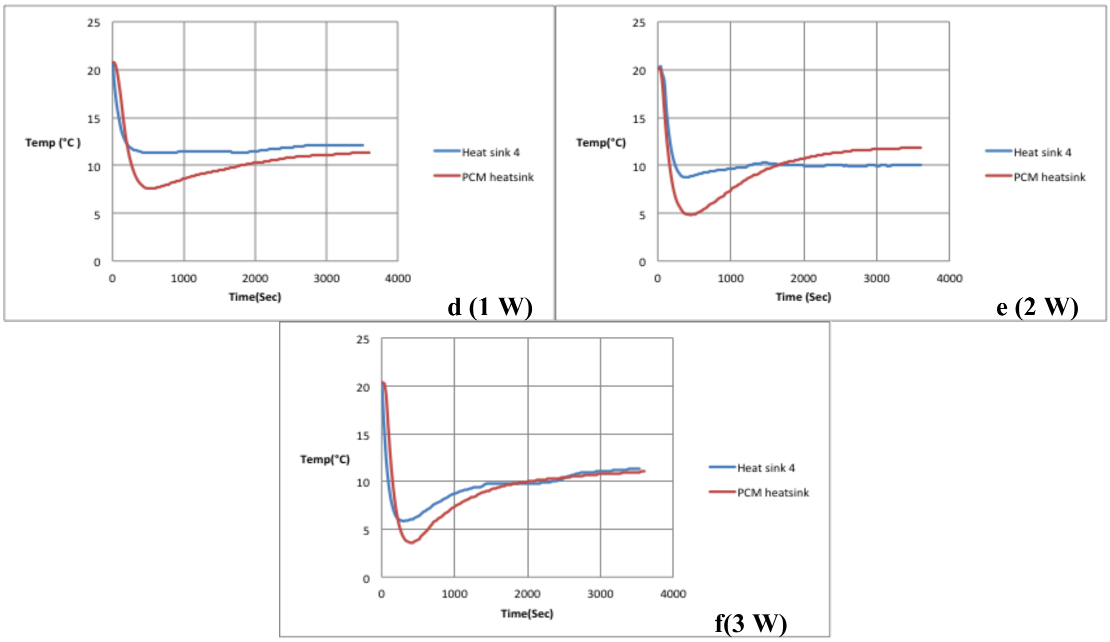


a (1 W)

b (2 W)

c (3 W)

Cold side



d (1 W)

e (2 W)

f(3 W)

Fig 3.10. Temperature profiles of heat sink 4 and PCM heat sink (HSU 5) during heating and cooling process at 1 W, 2 W and 3 W

Figures 3.10 (d), (e) and (f) illustrate the peltier cold side temperature variation of the two HSUs with time using 1, 2 and 3W.

As can be seen from figures 3.10 (d), (e) and (f) generally the PCM heat sink has a lower temperature than the HSU4 and the lowest reached temperature is about 5°C using 3W after about 5 minutes.

It can be concluded that by using PCM the temperature of the heat sink stabilises. The PCM heat sink temperature is increasing less rapidly compared to HSU4. This shows that by using a PCM-based heat sink as the cooling unit the thermal performance improves and the usage time of the portable cooling forearm device can be extended. The amount of used PCM determines the extension of the usage time. The larger PCM volume the more energy can be stored as latent heat and in this case the phase transition requires more time.

Based on both cold and hot side comparisons, the PCM heat sink has a better thermal performance.

3.3.3 Effect of insulation

The effect of using insulation around the PCM heat sink was investigated. A small polystyrene insulating box shown in figure 3.11 was inserted around the PCM HSU as can be seen in figure 3.12. Then a metal lid with 50 mm in length and 50 mm in width was inserted on top of the PCM heat sink to investigate the effect of closing the PCM box on the cooling process. This set of experiments has been done with a peltier model PE-031-08-15 with maximum power of 5.1W and maximum current of 2.2 Amps, with specifications shown in table 3.5. It was concluded from the previous section that PCM heat sink would enable cooling production at the lowest temperature for the time period required. Therefore testing of the PCM heat sink at conditions close to real life operation where the cooling device should be thermally insulated to avoid heat being transferred to other parts of the body and also may be covered with the patient clothing. This testing required a peltier device with high power input capability as that described above. At first three experiments were carried out using the insulating box around the PCM heat sink with different power inputs of 1, 2 and 3W for approximately 3600 seconds. Then three more tests were done with the same operational parameters but by using the lid on top of the PCM heat sink in addition to the insulating box around it.

The thermocouple under the top aluminium peltier holder was chosen for comparison of cold side temperatures and the thermocouple under the PCM HSU was chosen for hot side temperature comparisons.

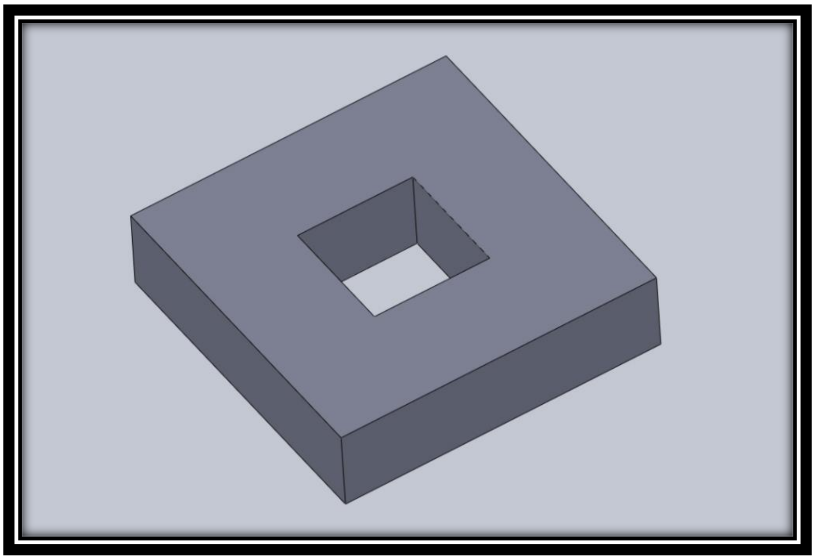


Fig 3.11. The small insulating box

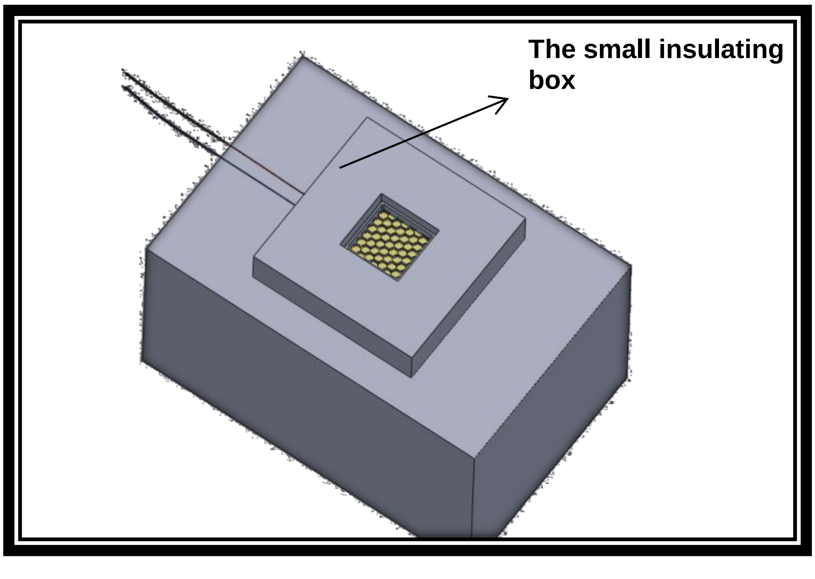


Fig 3.12. The small insulating box around the PCM heat sink

Table 3.5. PE-031-08-15 specifications

Peltier's type	**PE-031-08-15**
Delta T Max	74°C
Dimensions L × W × H	13 × 13 × 3.8mm
Maximum Current	2.2 Amps
Maximum Power	5.1 Watts
Maximum Temperature	85°C
Maximum Voltage	3.8 Volts
Number of Couples N	8

Figure 3.13 compares the peltier cold side temperature using PCM heat sink without insulation around it, with insulation and with insulation and lid for different power inputs of 1, 2 and 3W for approximately 3600 Sec while figure 3.14 compares the peltier hot side temperature for the same tests. As can be seen from figures 3.13 (a), (b) and (c) the PCM heat sink with insulation and lid reaches the lowest temperature which is about 2°C for 1 W and 0°C for 2 and 3 Watts, but it can only maintain those temperatures for only 200 Sec and then starts to increase to reach about 11°C after approximately an hour from the start of experiment for all the power levels of 1, 2 and 3 W. As the power increases to 3 W the temperature increases sharply and more rapidly after 3000 Sec for PCM heat sink with insulation and the lid. The PCM heat sink with insulation has the same pattern of temperature variation as the PCM heat sink with insulation and lid with lowest temperature of about 7°C for the power levels of 1W and 2 W, and 2°C for 3 W. It also did not maintain the low temperatures more than 200 Sec and the temperature increases rapidly to about 13°C for 1W, 15°C for 2W and 17°C for 3 W after an hour from the start of the experiment. The PCM heat sink without any insulation, which is called PCM heat sink without insulation and lid decreased to the temperature of 8°C for 1 W, 5°C for 2 W and 4°C for 3 W. Similar to the others the low temperatures were maintained for approximately 200 Sec and then started to increase but in this case the temperature did not increase that fast. It reached 11°C for 3 W after approximately one hour while the PCM heat sink with insulation reached 15°C and the PCM heat sink with insulation and lid reached 17°C at the same time and

power level. The results show that the PCM heat sink without any insulation is more stable and does not increase as rapidly as the ones that have the insulation. However, in the operation of the cooling device by patients, the PCM heat sink should be sealed and insulated to ensure safety of users.

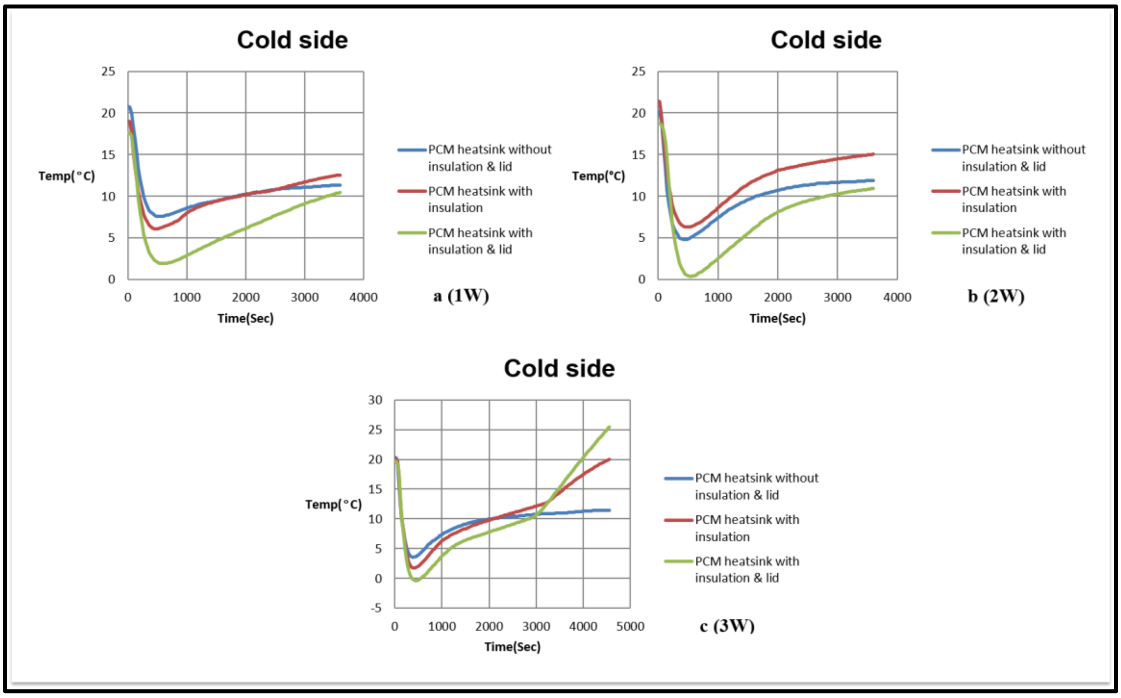


Fig 3.13. Temperature profiles of PCM heat sink without insulation &lid, with insulation, with insulation and lid during cooling process at 1, 2 and 3W

Figure 3.14 (a), shows that the power input of 1 W is not enough to melt the PCM and the PCM HSU without insulation and lid reached about 34°C after an hour. The other two reached about 37°C with the same operational parameters. The temperature of the solid PCM increased to its melting temperature of 42°C for the power inputs of 2 and 3 W as shown in figures 3.14 (b) and 3.14 (c). As can be seen from figures 3.14 (a) and 3.14 (c) the temperature of the PCM heat sink with insulation and lid which has the most insulation, increased to higher temperature values. Its temperature reaches about 61°C while the temperature of the PCM heat sink with insulation reached to about 55°C and the temperature of the one without insulation and lid gets to 45°C after an hour for the power level of 3 W.

In conclusion, both cold and hot side temperature comparisons show that the insulation causes a faster temperature increase so it can reduce the usage time of the portable cooling forearm wrap.

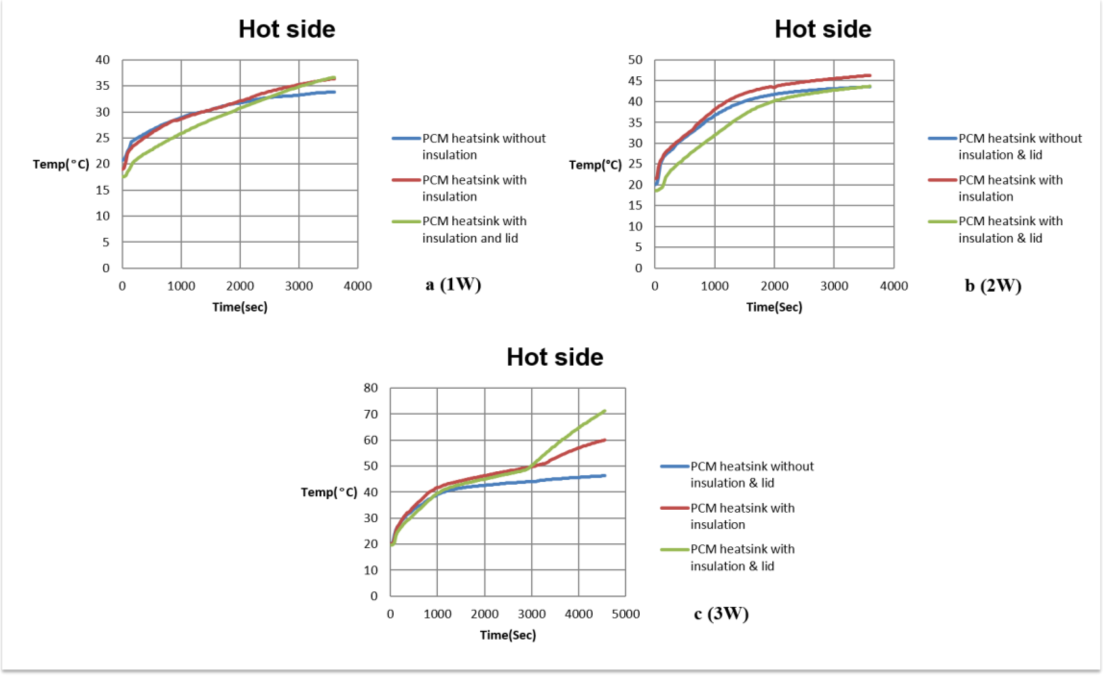


Fig 3.14. Temperature profiles of PCM heat sink without insulation &lid, with insulation, with insulation and lid during heating process at 1, 2 and 3W

3.3.4 Effect of PCM and insulation

In order to investigate performance of the heat sink 6 by using the insulation, the small insulating box was inserted around it and the lid was put on top of it. Then the results were compared to the experiment results of PCM HSU with box and lid to study effect of using PCM in conjunction with the insulation. The HSU 6 with box and lid tests were done for nearly 3600 Sec with different power inputs of 1, 2 and 3W at the same operational parameters used for PCM HSU with box and lid. Cold and hot side temperature comparisons for PCM HSU and HSU 6 with box and lid are shown in figures 3.15, 3.16 and 3.17.

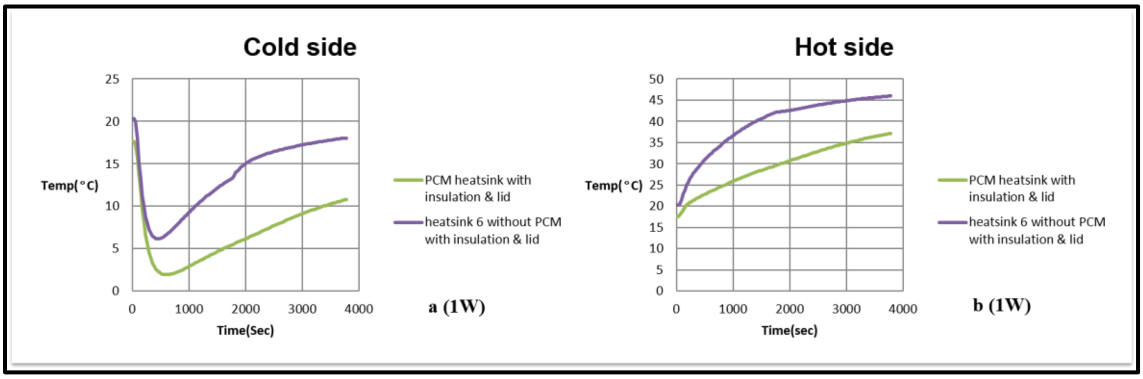


Fig 3.15. Temperature profiles of PCM heat sink with insulation and lid & heat sink 6 without PCM with insulation & lid during cooling & heating processed at 1W

As can be seen from both cold and hot side temperature comparisons for all the power levels of 1, 2 and 3W, the PCM heat sink has a significantly lower temperature profile compared to HSU 6 which is not filled with PCM.

Figure 3.15 (a) shows that the temperature of the PCM HSU reached 3°C and HSU 6 temperature reached 7°C. After 60 min the PCM heat sink temperature increased to 11°C while the temperature of the HSU 6 increased to 18°C. The temperature of the heat sink filled with PCM reached 37°C after an hour while the HSU 6 temperature increased to 46°C at the same time as shown in figure 3.15 (b). The input power of 1 W was not enough to melt the PCM.

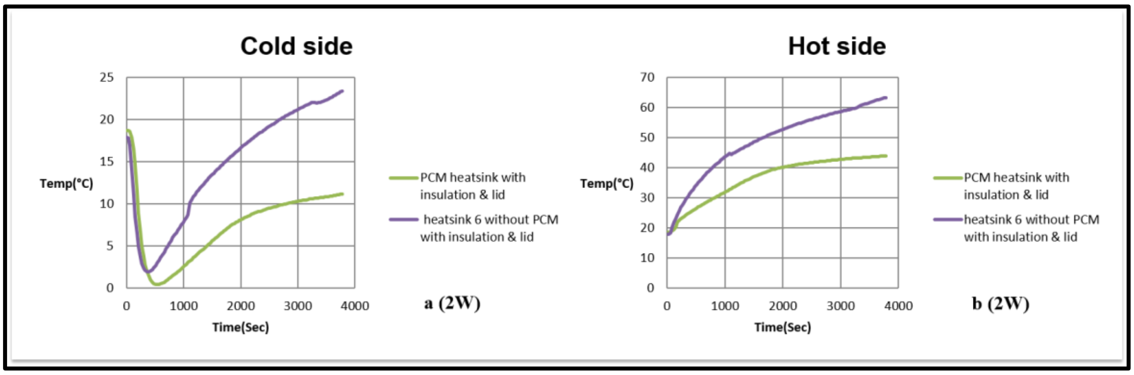


Fig 3.16. Temperature profiles of PCM heat sink with insulation and lid & heat sink 6 without PCM with insulation & lid during cooling & heating processed at 2W

Figure 3.16 (a) illustrates that the cold temperature with the heat sink filled with PCM insulated by the box and the lid, reached to nearly 0°C after 10 min with power input of 2 W and then increases to 11°C after an hour. With HSU6 the cold temperature reached 2°C after 7 min but it increases rapidly to reach over 20°C in one hour. Figure 3.16 (b) shows the hot side temperature profile of the PCM HSU can be divided into two regions. In region 1, the temperature of the solid PCM is increasing to its melting temperature for 44 min. In region 2, the phase change of the solid PCM happens and the temperature starts to stabilise as heat is used for melting (phase change) and hence stored as latent heat. The temperature is still increasing but slowly as the PCM has a poor thermal conductivity. The hot side temperature with the HSU6 increased to 63°C after an hour while the temperature of the PCM HSU reached to 44°C after a time of 60 min, which is 19°C lower than the HSU 6 at the same time.

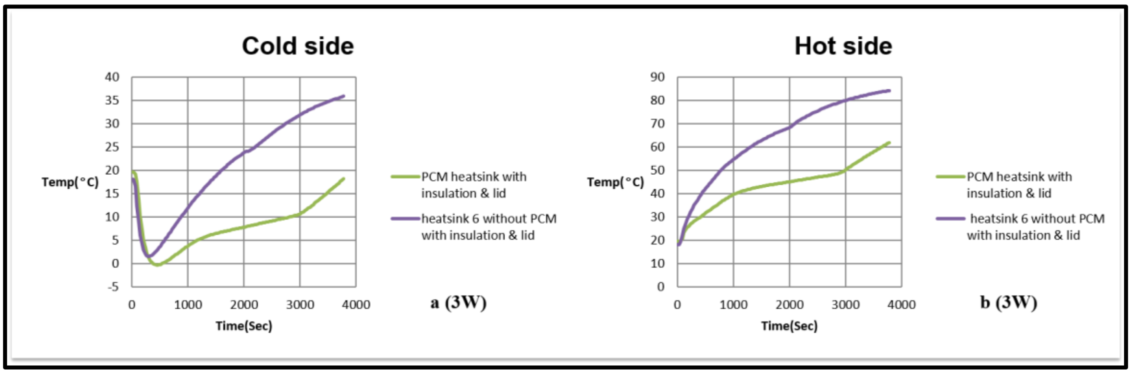


Fig 3.17. Temperature profiles of PCM heat sink with insulation and lid & heat sink 6 without PCM with insulation & lid during cooling & heating processed at 3W

As can be seen from figure 3.17 (a), with PCM HSU the peltier cold temperature decreased to −0.05°C after 9 min and then it increased to 17°C after an hour. With the HSU 6 it decreased to 2°C after 4 min and then it increased sharply to 36°C after an hour which is nearly twice more than the temperature reached by the PCM HSU after a time of 60 min.

Figure 3.17 (b) illustrates that the peltier hot side temperature with the PCM HSU is considerably lower than the temperature of the HSU 6 that is without PCM. HSU 6 temperature increases to 83°C after 60 min while with the PCM heat sink the temperature is 60°C that is 23°C lower at the same time of 60 min and is still increasing. This shows the benefit of using PCM where after the melting point of the PCM (42°C), the PCM heat sink is notably cooler (31°C cooler after 48 min of heating) through the heating phase than HSU 6 that is without PCM. This is because of the large amount of latent heat absorbed by PCM when it starts to melt at 42°C, which results in better cooling performance of the heat sink.

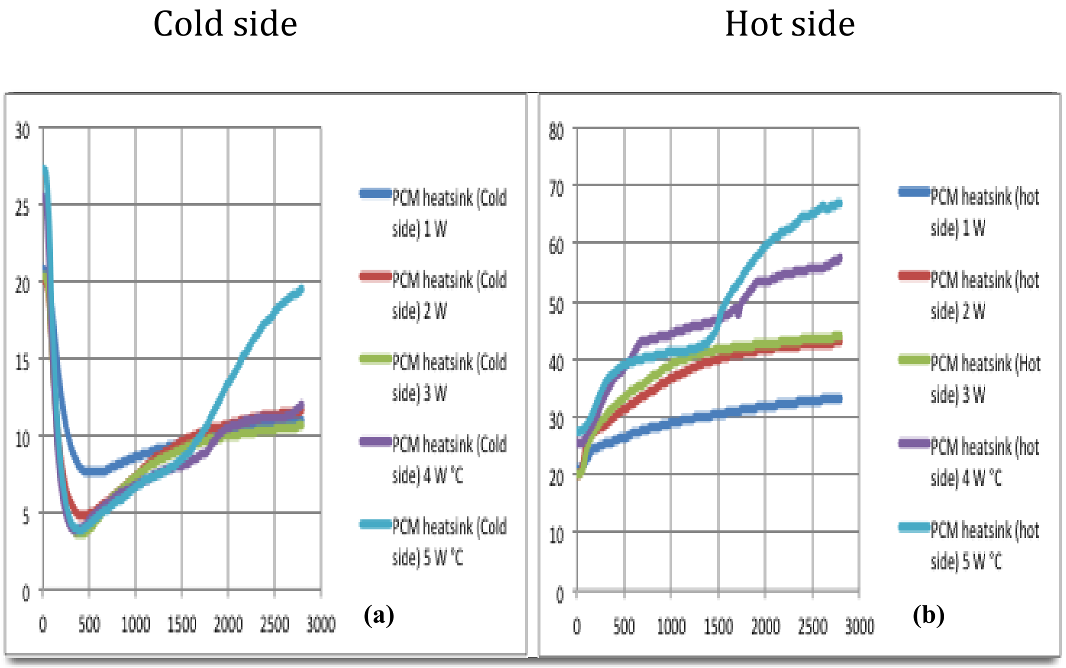
The temperature profile of the PCM HSU in the figure 3.17 can be divided into three regions. In region 1, the temperature of the solid phase change material is increasing quickly to its melting temperature of 42°C. In the second region, the PCM starts melting and temperature remains relatively constant as the heat is used for melting. The temperature is still increasing due to poor thermal conductivity of PCM. As the PCM melts more thickness of the liquid layer increases and the heat transfer rate decreases. In region 3, the temperature starts to increase again once the PCM is fully melted. It took 22 min to finish region 1 and 26 min to complete stage 2.

It can be summarized from figure 3.17 that the PCM HSU has a more stable temperature profile compared to heat sink 6 which is not filled with PCM. The maximum temperature difference between the two HSUs is 30°C. The temperature of the PCM heat sink is increasing more slowly. This shows that by using PCM based heat storage unit in the cooling system the usage time of the forearm cooling device can be increased. Increasing the amount of the used PCM would result in increasing the PCM heat capacity and storing more energy as latent heat which means that extra time will be needed for phase transition so the volume of the used PCM affect the length of the usage time of the portable forearm cooling device.

In conclusion the PCM HSU or heat sink 5 without any insulation had the best thermal performance compared to the other heat sinks. In addition to the mentioned reasons, the heat sink with PCM has the largest surface area compared to heat sinks 1, 2, 3 and 4 while its difference with HSU 6 is containing PCM which causes to keep the cold temperature for longer period.

3.3.5 Effect of power level

After specifying the PCM heat sink as the best performing HSU compared to the others, it was tested with power inputs of 4 W and 5W for 2790 Sec to investigate the effect of power levels on its performance. Then the results were compared to the experiments done for the PCM HSU with power levels of 1 W, 2 W and 3 W. Figures 3.18 (a) and 3.18 (b) show the temperature variations with time during the cooling and heating phases using different power inputs of 1 W, 2 W, 3 W, 4 W and 5 W for 2790 Sec (46.5 min). The thermocouple under the top aluminium peltier holder recorded the cooling phase temperatures and was named as cold side in figure 3.18 (a). A thermocouple between the fins recorded the heating phase temperatures and named as hot side in figure 3.18 (b).


Cold side

Hot side

Fig 3.18. Temperature profile of PCM heat sink during cooling and heating process at 1 W, 2 W, 3 W, 4 W and 5 W

Figure 3.18 (a) shows that the cold side temperature with power input of 4 W and 5 W decreased to as low as 3.84 after about 7 minutes, although it increased fast to 11.92°C after 46.5 min using 4 W and with 5 W the temperature increased steeply to 19.53°C after 46.5 min.

Figure 3.18 (b) illustrates that the PCM starts to melt earlier with increasing the power level. The maximum temperature attained after 46.5 min at 1 W was 33.06°C, at 2 W was 42.92°C, at 3 W was 43.83°C while the maximum temperature at 4 W and 5 W was 57.72°C and 67.01°C respectively.

The results show that after 46 min of process using a power input of 5 W, the temperature of the PCM heat sink increases sharply, which will make the use of forearm cooling device uncomfortable for the MS patient. Thus to improve the thermal conductivity of PCM and the performance of cooling system, the optimisation of the heat sink is needed.

3.4 conclusion

The results show that the PCM based heat sink with insulation and lid was able to produce cooling below 10°C for about an hour. Power input of 3 W is enough to achieve this cooling temperature.

Chapter 4: *Cooling Performance of Three Peltier With Various Phase Change Materials*

4.1 Introduction

The second set of experiments was carried out using three peltiers to generate higher cooling effect. A heat sink on the TEC module had to be installed to achieve reliable cooling, so phase change material was used instead to absorb the heat rejected from the peltier. Consequently TEC is able to enhance the effective working time and keep steady during the working period. Two different phase change materials ranging from 37 to 42°C were used namely PCM-OM37P and Paraffin wax (Rubitherm-RT42) to investigate the best performing one. Then the cooling loads that can be achieved using different power inputs were calculated.

The third set of experiments was conducted using three peltiers in cycles of on and off processes to ensure that the test results are repeatable and in order to analyse the temperature changes in the PCM after heating for a certain time and cooling afterwards.

4.2 Three peltier test facility

To develop a forearm cooling system for MS patients, a number of peltier devices will be needed to achieve the required cooling load. These peltier devices extract heat from the forearm and reject it to heat sink units. In this section the performance of three peltier devices was investigated using test facility shown in figure 4.1.

The test facility consists of the following components:

- A DC power supply
- Two aluminium boxes one container has water and the second one has PCM
- Three peltiers (PE-031-08-15) fitted between the aluminium boxes
- Two Pico data loggers (TC-08), T type thermocouples and a computer

As can be seen in figure 4.1 and 4.2, the power supply is connected to the three peltiers that are sandwiched between the aluminium boxes. The schematic diagram of the experiment set up for second sets of tests is shown in figure 4.2 and a cross section of cooling device is shown in figure 4.3. The peltier thermoelectric coolers are fitted in between the aluminium boxes using a thin layer of the OMEGATHERM OT-201 thermal paste on both sides of the peltiers. All the three thermoelectric coolers are PE-031-08-15 with maximum power of 5.1 W and maximum current of 2.2 Amps with their specifications given in table 3.4. The adjustable DC power supply used, is the same as the one used for the single peltier tests to control the power input to the peltier device. One of the aluminium boxes is filled with water simulating the upper limb of the MS patient and the other one contains PCM as the heat storage part. Both aluminium boxes had the same external dimensions of 160 mm in length, 25 mm in width, 12.4 mm in height and wall thickness of 2 mm. There was a rectangular opening at one side of each aluminium box to enable filling the aluminium containers with PCM and water. The rectangular opening is 23 mm in width and 10.40 mm in height. The view of the peltiers and the rectangular opening on the aluminium box is shown in figure 4.4. The front view of the PCM filled aluminium box and the bottom view of the water filled aluminium box is illustrated in appendix.

Seven thermocouples were placed in the PCM filled aluminium box and two thermocouples in the water filled box. Two thermocouples were placed on the aluminium boxes, one on the PCM filled box and another on the water filled one. One thermocouple was placed in the data logger to measure the ambient temperature. More explanation about the number, name and installation of thermocouples is in section 4.2.2. To have a better understanding of aluminium box dimensions, place of the peltiers and the holes locations for the thermocouples in water and PCM filled aluminium boxes views and drawings that were done using CAD have been inserted in section 4.2.2. PCM filled aluminium box was located on the heat release side of the peltier while the water filled one will be on the cold side.

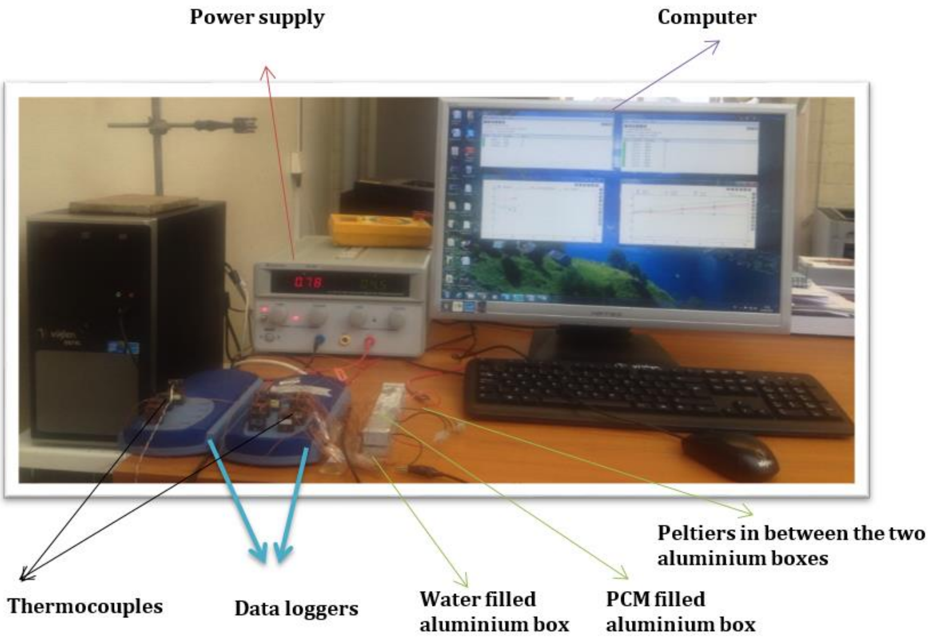


Fig *4.1. Experiment set up of the second set of tests*

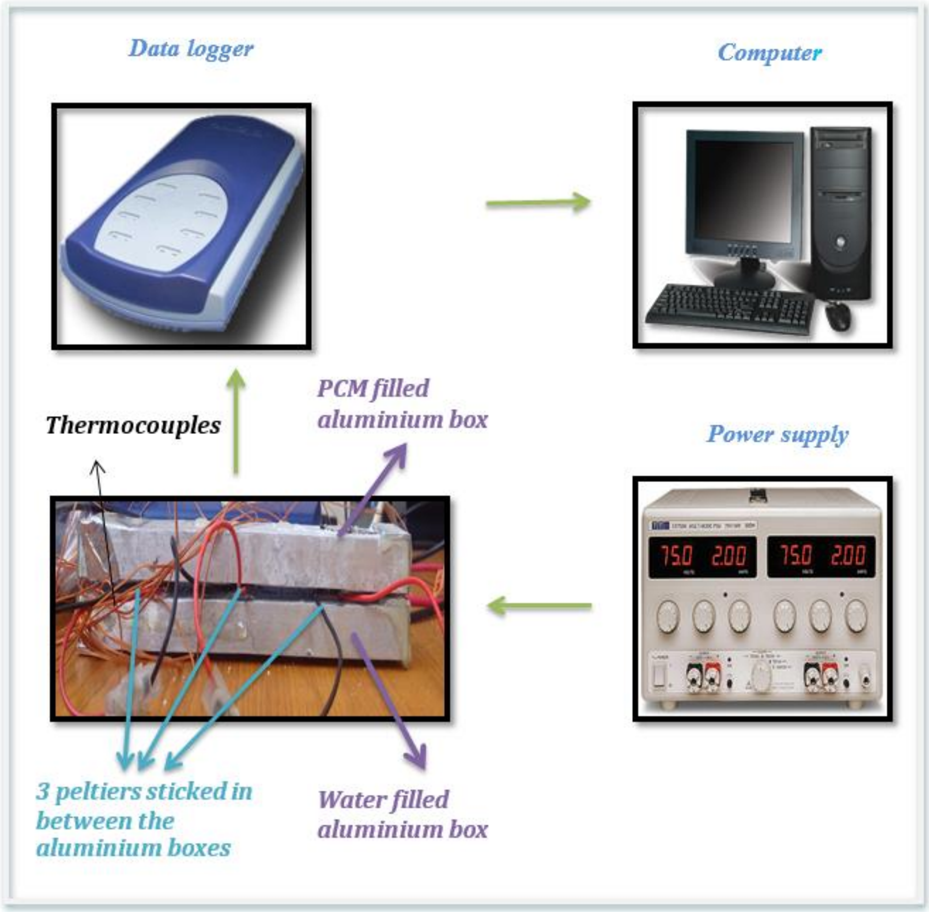


Fig 4.2. The schematic diagram of the experiment set up for second sets of tests

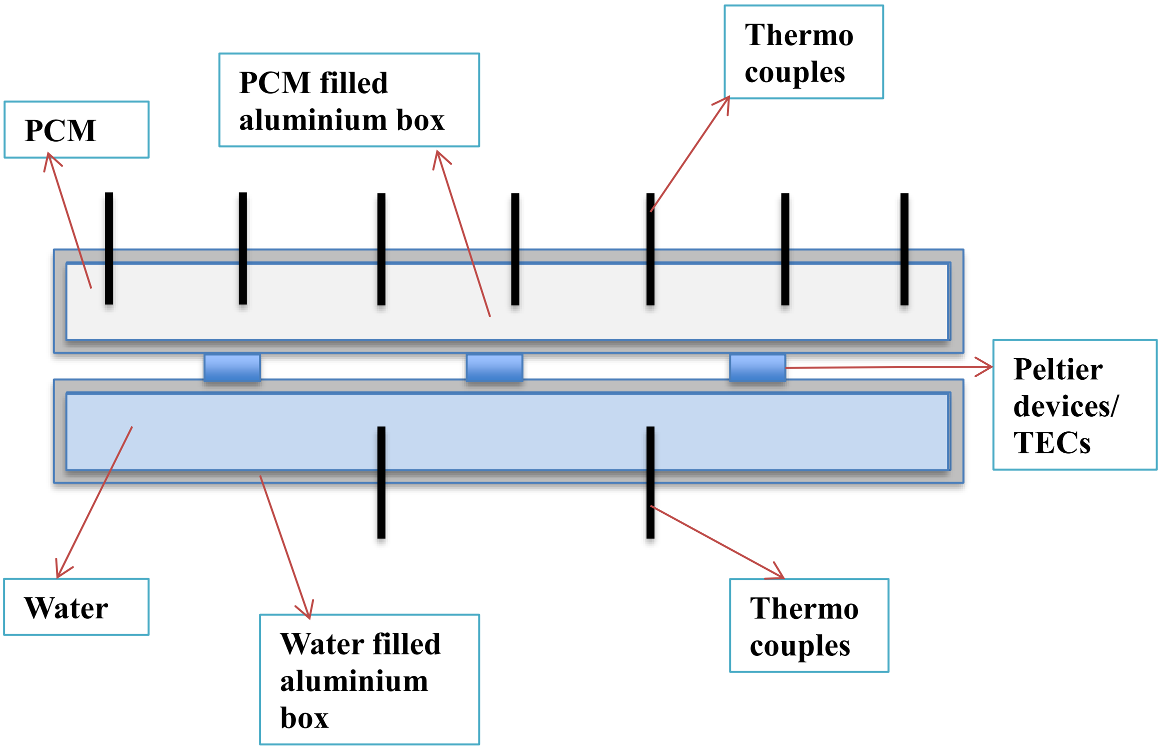


Fig 4.3. Cross section of cooling device

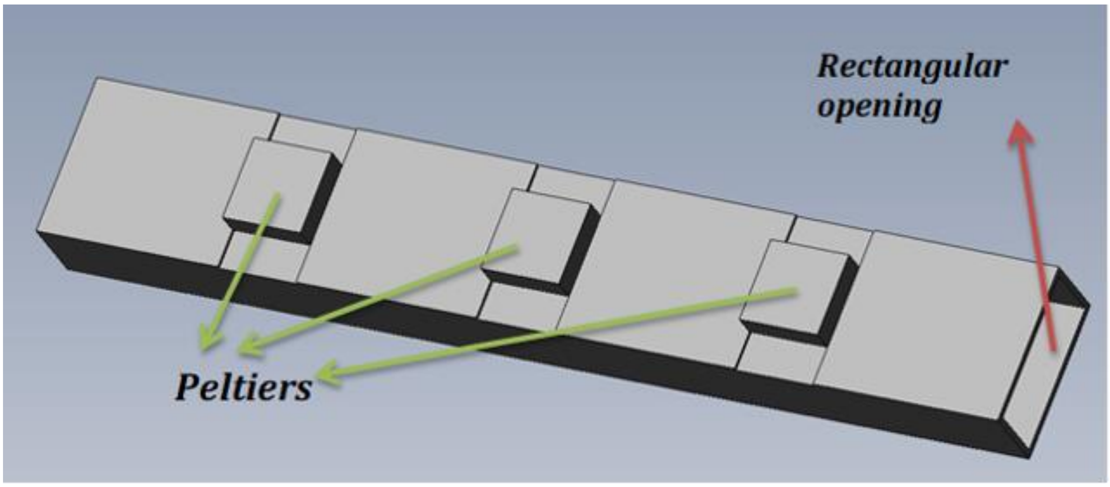


Fig 4.4. The view of the peltiers and the rectangular opening on the aluminium box

4.2.1 Phase change materials (PCM)

Two different PCMs with melting temperatures ranging from 37 to 42°C were selected from organic materials to maintain the maximum operating temperature of the device within safe values. For selecting the PCM there are important characteristics that need to be considered namely, latent heat of melting, volume changes, melting temperature, heat conductivity, cost and reusability. High latent heat of melting will increase the length of phase change process so the temperature can be kept for longer period [21].

Table 4.1 shows the characteristics of the two PCM materials used. The PCMs were supplied by RGEES, LLC in USA. Paraffin wax (Rubitherm RT-42) and OM37P are the organic materials.

Table 4.1. PCMs characteristics comparison

SavEnrg^{TM} PCM	**Phase Change Temperature (°C)**	**Phase Change Temperature (°F)**	**Density (Kg/m^3)**	**Latent Heat (KJ/Kg)**	**Quantity (Kg) needed to store 1 KWh**	**Max. Operating Temperature (°C)**	**Viscosity (kg/ms)**
PCM-OM37P	37	99	880	218	17	80	0.0485
Paraffin wax (Rubitherm RT-42)	42	107	880	174	N/A	N/A	N/A

Phase change materials can be divided into two main groups of organic and inorganic. Inorganic materials are non-flammable and cheaper compared to organic PCMs but their sub-cooling and phase segregation should be taken into consideration as it may affect the thermal performance of PCM and causes extra expenses. When the inorganic material solidifies below the melting point sub-cooling happens so stabilizers and nucleating agents will be needed to overcome the issue. They have high density, high latent heat and higher thermal conductivity.

Organic materials contain carbon in their ingredients. From the information given by RGEES, LLC, organic PCMs have higher latent heat but lower viscosity, lower density and need less quantity of mass to store 1KWh compared to the inorganic PCM. They are also more chemically stable, do not have sub-cooling and phase segregation. However, they are flammable and have low thermal conductivity.

It can be concluded that the organic PCMs have better material characteristics and are theoretically more suitable to be used in the cooling application of forearm.

4.2.2 Instrumentation

The PCM and water boxes were instrumented with thermocouples to measure their temperature. T type thermocouples were inserted into the boxes through holes drilled in the walls of the aluminium boxes.

There were seven holes drilled on topside of the PCM filled aluminium box and two on the bottom side of the water filled aluminium container. Seven thermocouples were used in the PCM box to capture the temperature variation in the PCM. As water has significantly higher thermal conductivity than the PCM, the temperature variation within the water box is less significant compared to temperature variation within the PCM box. The diameter of each hole was 0.5 mm. Also one thermocouple was inserted on top of the PCM filled aluminium box and named as “on PCM filled box”. Another was placed on top of the water filled one and named as “on water filled box”. “Water_in1” and “Water_in2” are names of the thermocouples inside the water filled aluminium box. The seven thermocouples inside the PCM filled aluminium box are labelled as PCM1, PCM2, PCM3, PCM4, PCM5, PCM6 and PCM7. To understand the exact place of the thermocouples, PCM and water filled aluminium boxes with holes for placing the thermocouples are shown in figures 4.5 and 4.6.

As each data logger has eight channels, two data loggers were needed enable recording all the temperatures. The mentioned thermocouples are connected to the data logger, which in turn is connected to the computer and the thermocouple temperatures are read by PicoLog software.

The peltiers were connected in series so the current was the same for all the three thermoelectric coolers, but the voltage was divided between them. The voltages applied to the peltiers were measured using voltmeter to ensure that the voltage shown on the power supply is the same as sum of the voltages measured with the voltmeter. The voltages measured by both devices were approximately the same.

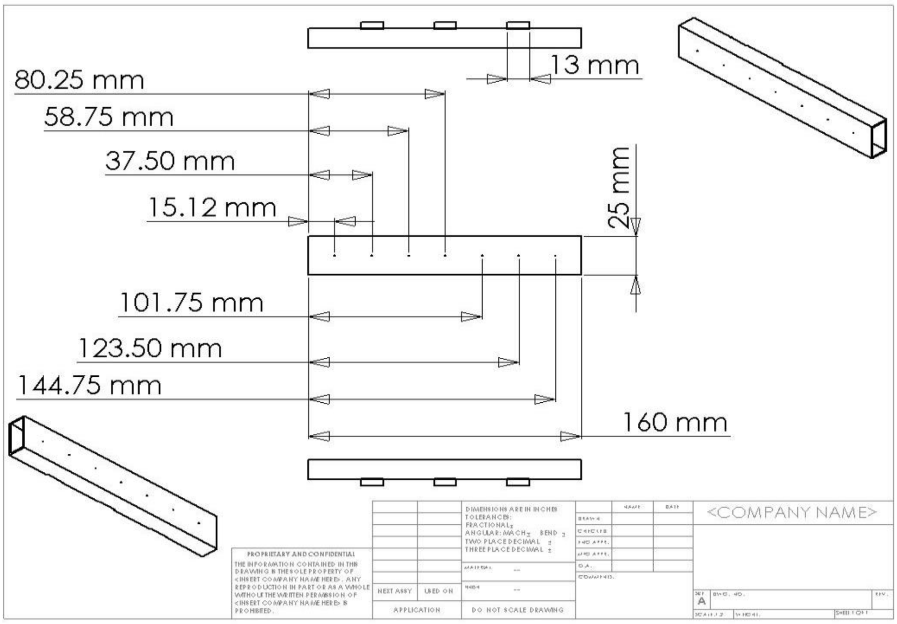


Fig 4.5. Back view of the PCM filled aluminium box with thermocouple holes

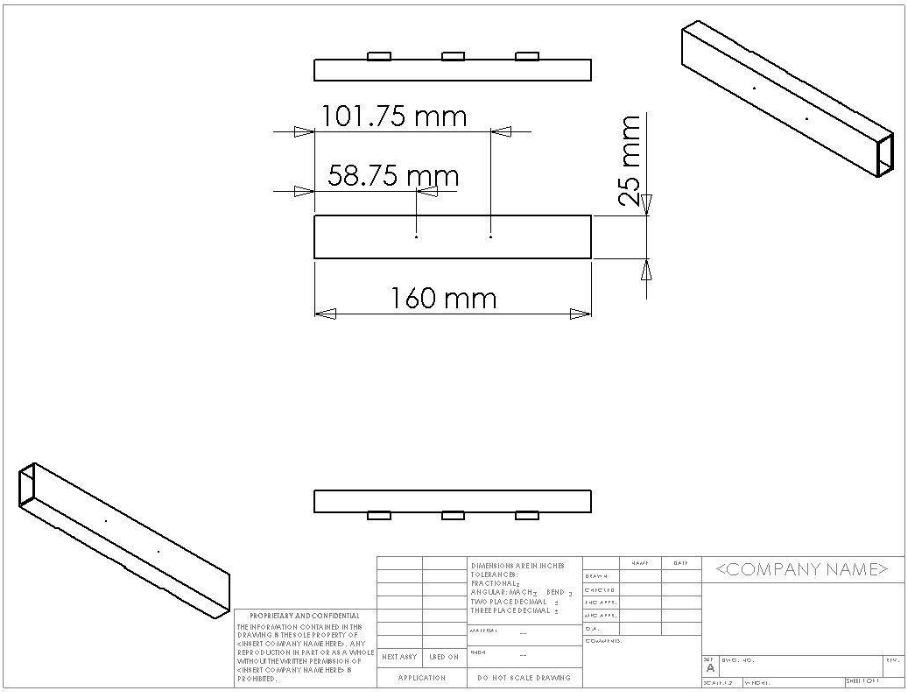


Fig 4.6. Bottom view of the water filled aluminium box

4.3 Results

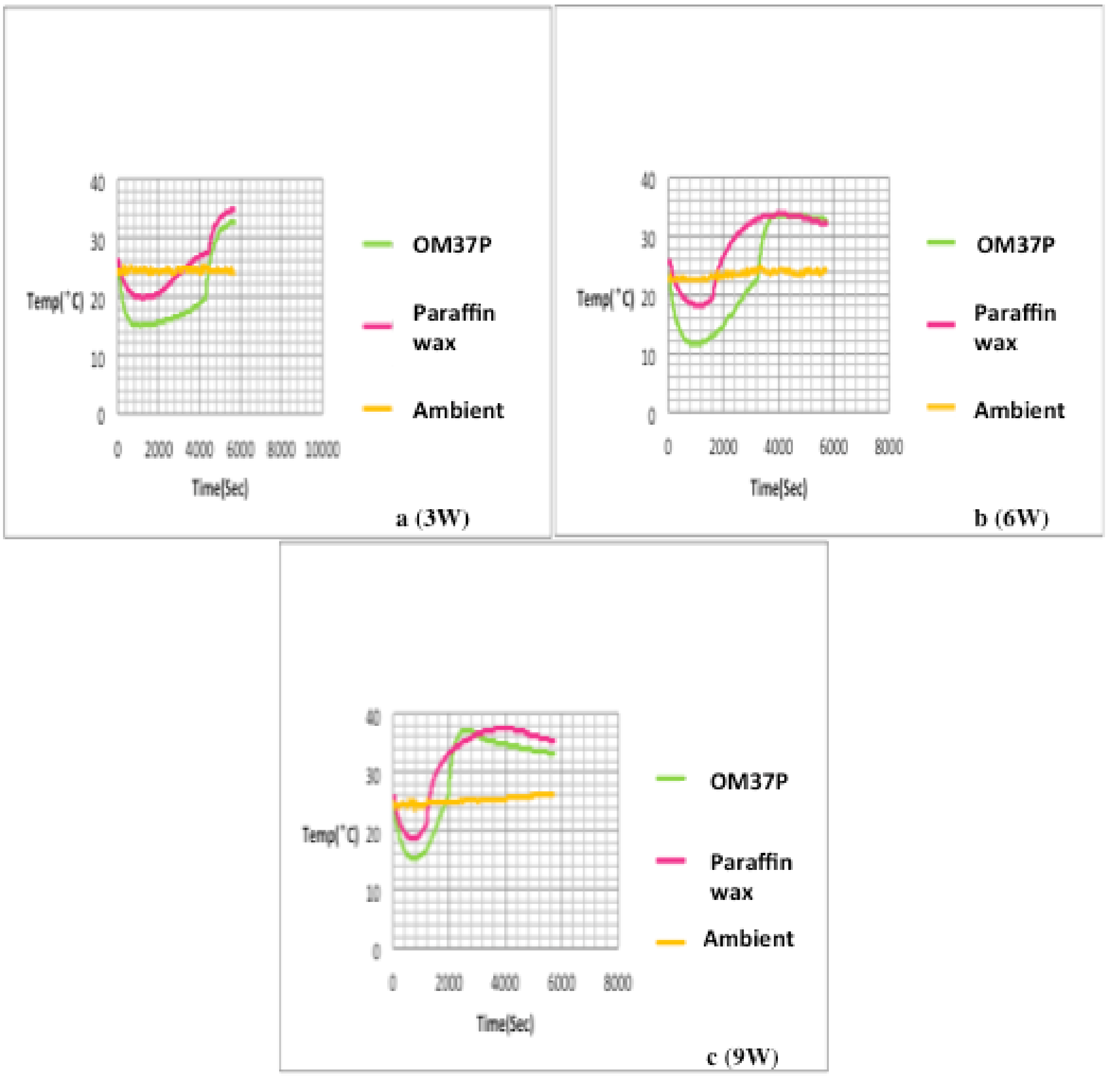
This experimental study was carried out to investigate the performance of three peltiers using two phase change materials (paraffin wax and OM37P) as heatsinks. PCM has been chosen to extract the heat from the hot surface of the peltier and water has been used to represent the cooling load associated with the forearm. The effect of different power levels of 3 W, 6 W and 9 W was studied. At the end, cooling load calculations were carried out for OM37P using 3 W, 6 W and 9 W to understand how much heat can be rejected by the peltier to the PCM box. After that Coefficient of performance (COP) of the peltier was calculated.

4.3.1 Effect of different PCMs and power levels

OM37P and paraffin wax cold and hot sides with different power inputs of 3 W, 6 W and 9 W compared together to study the effect of different power levels and to investigate which PCM can cool down to the desired temperature (18°C) and can maintain it for longer time. The duration of this set of tests was about 5800 Sec (96 minutes).

Figures 4.7 and 4.8 compare the peltiers cold and hot side temperatures using OM37P and paraffin wax at power inputs of 3, 6 and 9 watts respectively over a period of about 5800 seconds.

As can be seen from figure 4.7, PCM OM37P reached a lower temperature using all power inputs of 3, 6 and 9 watts compared to paraffin wax PCM. OM37P PCM using power input of 6 W decreased to 11.66°C after 17 minutes while the lowest temperature reached by paraffin wax is 18.27°C. The temperature of 11.66°C achieved by OM37P using 6 W is the lowest temperature attained compared to 3 and 9 W, although it increases to 32.82°C after about 96 min.



a (3W)

b (6W)

c (9W)

Fig 4.7. Peltier cold temperature profiles of OM37P & paraffin wax during cooling process at 3, 6 and 9W

Figure 4.8 shows that as the power level increases the PCM start to melt earlier.

As can be seen from figure 4.8, Paraffin wax increases to a higher temperature at all power levels supplied compared to OM37P. For example, the maximum temperature for OM37P attained after 20 min at 3 W was 36.88°C, at 6 W was 41.65°C and at 9 W was 55.03°C while for paraffin wax at 3 W was 41.72°C, at 6 W was 51.26°C and at 9 W was 69.44°C respectively.

The results show that OM37P reached to a lower temperature compared to paraffin wax for both cold and hot sides which makes it a suitable PCM to be used in the forearm cooling device.

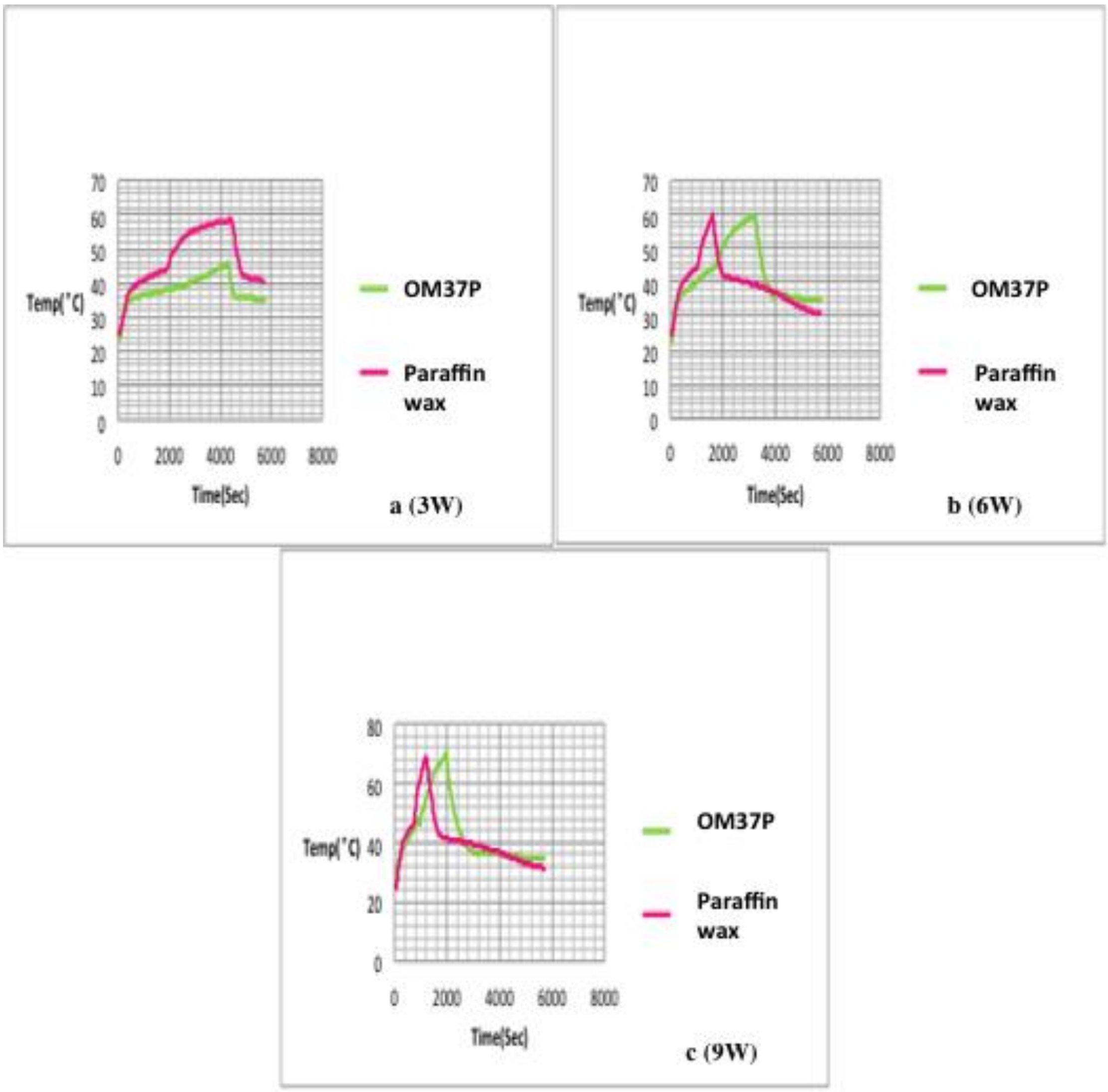


Fig 4.8. Peltier hot temperature profiles of OM37P & paraffin wax during heating process at 3, 6 and 9W

4.4 Cooling load, coefficient of performance (COP) and heating load at 3, 6 and 9 W for OM37P

As OM37P PCM reached to a lower temperature compared to paraffin wax, it is a better PCM material to be used in forearm cooling device. Thus, the cooling load, COP and heating load were calculated for OM37P in second set of experiments.

Calculations for cooling load using experimental results shown in figure 4.9 at 3, 6 and 9 W, can be achieved by dividing cooling energy in joules (J) by total time took to reach the minimum temperature that is 1035 Sec using 3 W, 1058 Sec using 6 W and 716 Sec using 9 W. Cooling energy for 3 W is 1740.89 J, for 6 W is 2190.34 J and for 9 W is

1867.95 J. Cooling energy was calculated by sum of heat transfer (dQ) during 1035, 1058 and 716 seconds using 3, 6 and 9 W respectively. So the cooling load shown in equation (4.1) at 3 W will be equal to:

$$Qe \text{ (Cooling load)} = \frac{Cooling\ energy\ (J)}{Time\ (S)} = \frac{1740.89}{1035} = 1.68 \text{ W} \qquad (4.1)$$

The efficiency of the peltier cooler is described by the coefficient of performance (COP) that is expressed by equation (4.2) [30]. The power 3, 6 and 9 W is the power input to the peltier in experimental work. Therefore the COP at 3 W will be cooling load divided by power input:

$$\text{COP} = \frac{\text{Qe}}{P} = \frac{1.68}{3} = 0.56 \qquad (4.2)$$

The sum of power and the cooling load will be the heat rejected by the peltier to the PCM box (Heating load, Q_{toatl}) that is shown in equation 4.3.

$$Q_{total} = Q_{input} + Q_e \qquad (4.3)$$

$$= 3 \text{ W} + 1.68 = 4.68 \text{ W}$$

So, at power of 3 Watt to the peltier, a total of 4.68 W of heat should be rejected.

Table 4.2 illustrates the cooling load, COP and heating load supplied to the PCM box in different power inputs. The COP decreased with increasing the power.

Table 4.2. Calculation of cooling load, COP and heating load supplied to PCM

Power input, Q_{input} (W)	**Cooling load, Q_e (W)**	**COP**	**Heating load, Q_{total} (W)**
3	1.68	0.56	4.68
6	2.07	0.34	8.07
9	2.60	0.28	11.60

4.5 Cyclic results

For MS patients, the cooling device will be used intermittently i.e. for short periods of time when the heat dependant intention tremor symptoms are severe or when the patient needs to carry out some daily routines. Therefore, it is important to test the cooling device during cyclic operation. In third set of the tests, the device will be turned on for a period of time and then switched off for a similar period of time to allow the PCM material to cool down. The device will be turned on for a period of time that is 1800 seconds so heat will be extracted from the water box and rejected to the PCM box. When heat is emitted to the PCM, its temperature will rise to the melting point so it will start melting and then the liquid PCM temperature will increase. As a result of increasing the temperature of PCM, the water box temperature also increases therefore to enable cooling of the PCM material the peltier device should be turned off for 1800 seconds. So, the device will be functioning on a cycle of on and off processes. Figures 4.9 and 4.10 show the temperature variation of the water and OM37P phase change material in cycles of on and off processes using power inputs of 3 and 6 W. Each cycle is 3600 seconds that includes 1800 Sec of switching on and 1800 Sec of switching off the device.

The device will be switched on for 1800 sec and then switched off for the same amount of time for each cycle (cycle of on and off processes). With power input of 3 W, water temperature will decrease to 16°C at time of 1004 sec. OM37P PCM temperature will increase to 37°C which, is the melting temperature of OM37P at time of 938 sec. After that the OM37P temperature will increase to 39.29°C at time of 1771 sec. Then after 1800 sec the device will be switched off for 1800 sec and then will be turned on again for the second cycle for 1800 sec. During the off period, the water temperature increases to 30.65°C while the PCM box cools down to 33.56°C. Repeating the cycle of 1800 sec on and 1800 sec off shows that the temperature reached by the water box increased from 16°C in the first cycle to 18°C in the second cycle, to 19°C in the third cycle and then remained constant at 20°C in the fourth and fifth cycles. Also, the highest temperature reached by the PCM box showed an increasing trend with the maximum temperature reached 46.46°C. The minimum PCM temperature also shows an increasing trend but remains below the melting temperature of 37°C. It can be concluded that with 3 W power input, the device was able to maintain the temperature of the water box around 5°C below the ambient temperature.

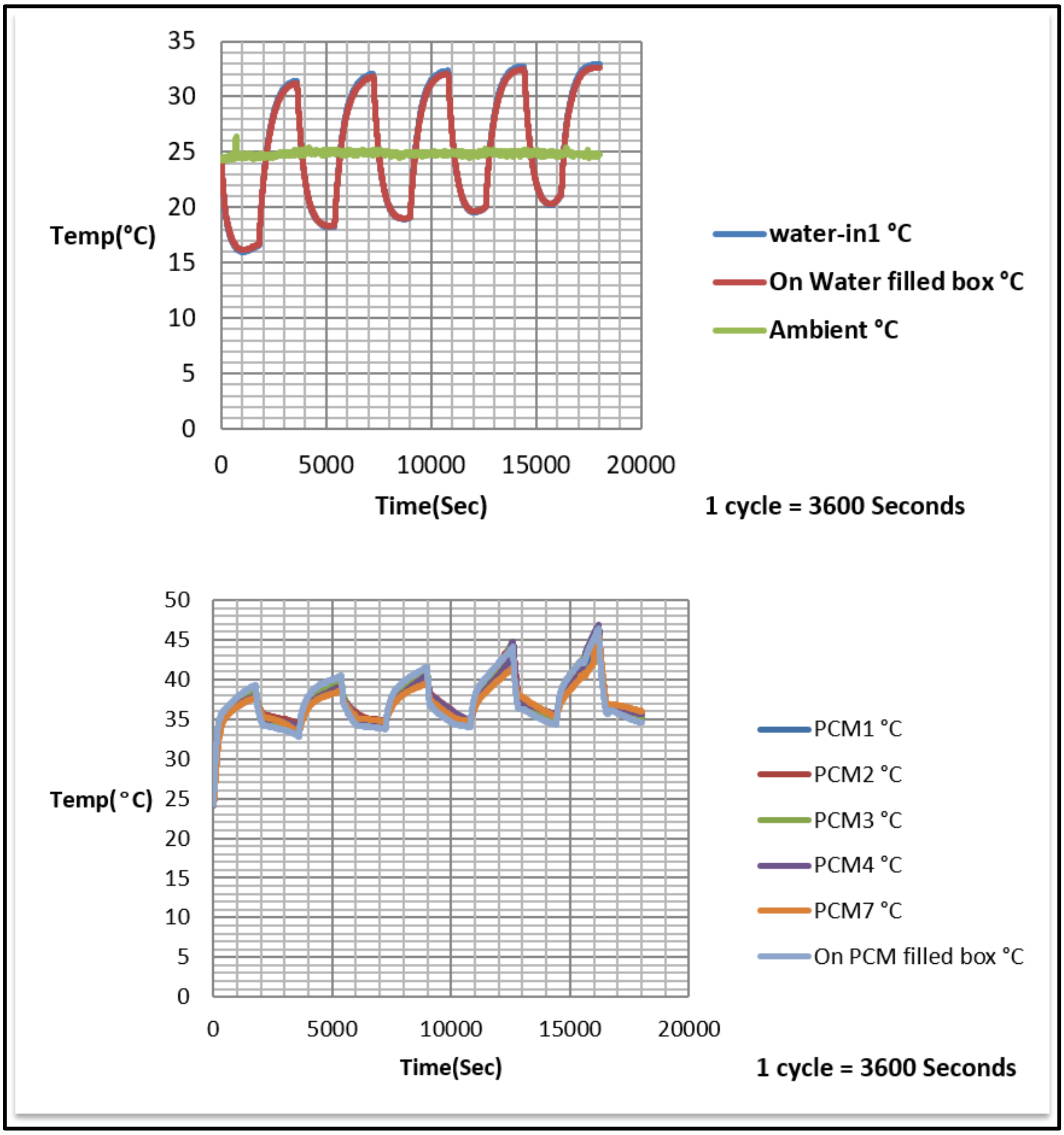


Fig 4.9. Temperature variation on 5 cycles for water and OM37P PCM using 3 W

With 6 W, the water lowest temperature increases from 15°C in cycle 1 to 22°C in the second cycle and then remains around 25°C in the third, fourth and fifth cycle. As for the PCM temperature, it heats up until the maximum temperature of 62.21°C at time of 16200 sec and at time of 18000 sec, the OM37P temperature is decreased to 35.95°C. The PCM temperature remains higher than the melting point during cycles 2, 3, 4 and 5. This indicates application of 6 W will produce cooling only during the first cycle.

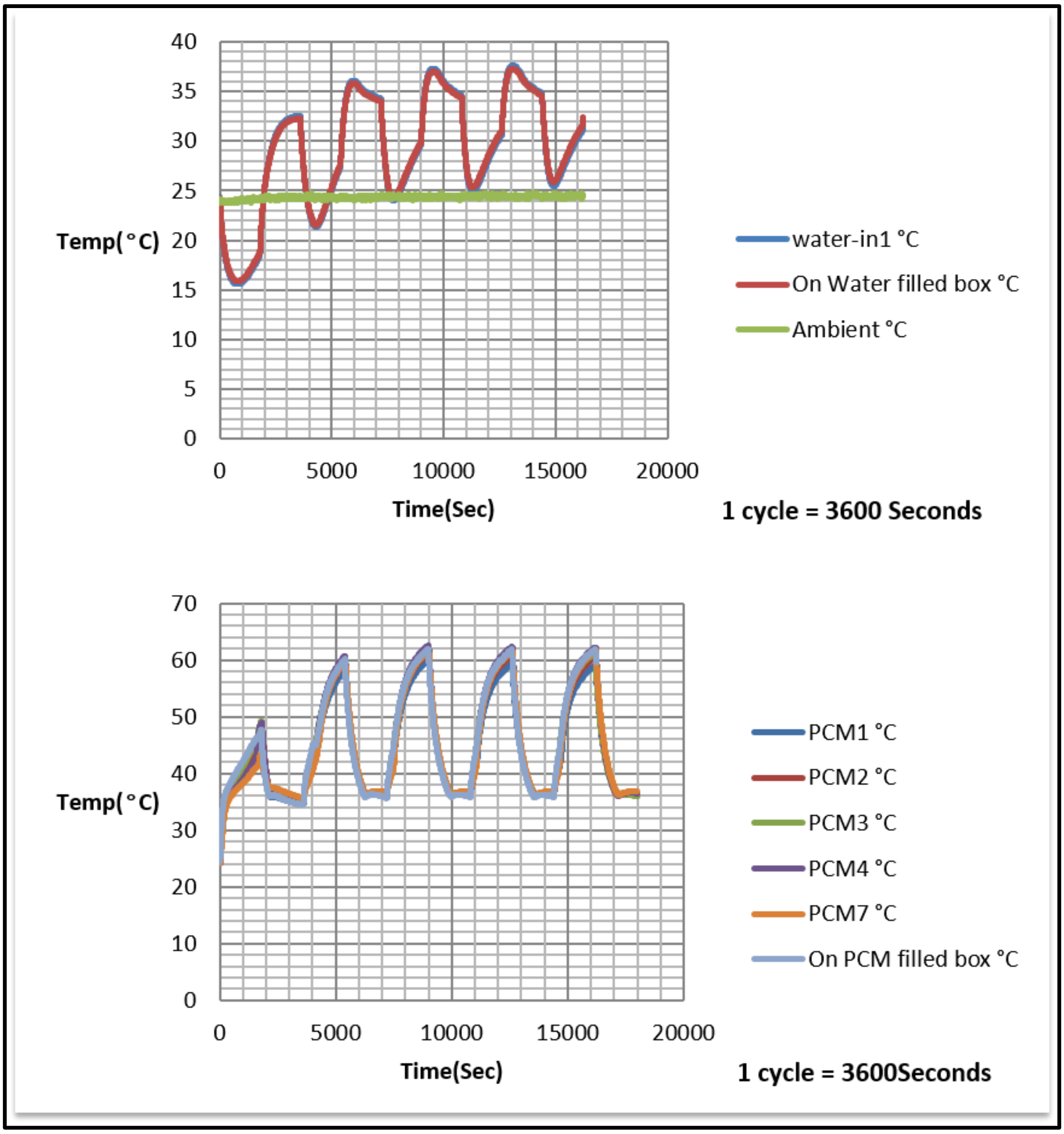


Fig 4.10. Temperature variation on 5 cycles for water and OM37P PCM using 6 W

4.6 Conclusion

A lightweight and compact wearable cooling device for MS patients is needed to alleviate the symptoms like intention tremor, heat intolerance and fatigue initiated by physical activities or increased ambient temperature. This project investigated using the combination of peltiers with PCM materials to decrease the temperature to 11.66°C for period of 17 minutes. The results illustrated that PCM OM37P with power input of 6 W to the thermoelectric coolers has the capability to attain such requirement.

Chapter 5: *Discussion, Conclusion and Future Work*

Multiple sclerosis (MS) is an immune-mediated disease of the central nervous system (CNS), which attacks the myelinated axons in the CNS and destroys the axons and myelin. Symptoms such as vision problems, difficulties in walking, fatigue, muscle spasms, ataxia and tremor are often experienced in MS patients.

Around 75% of people with MS experience a tremor. Tremor is an alternating and involuntary movement that can affect the muscles of any part of the body. There are two types of tremor, Intention and Postural tremor. Intention tremor is characterised by a slow shaking that occurs at the end of an intended movement, most noticeably in the hands. When the temperature or heat in the body increases, symptoms will get worse temporarily. There is no known cure for MS, but the effects of manipulating the internal thermal condition of MS patients have been reported. One useful method is extracting heat from the patient’s body through specialized subcutaneous vascular structures that underlie the non-hairy skin surfaces of the human body on their upper limbs; hand and forearm that improves MS patient’s daily life performances.

Published medical research based on clinical trials showed that cooling the forearm outer skin down to 18°C for period of 15 minutes can reduce tremor. It also illustrated that tremor reduction continued throughout 30-minute post cooling evaluation phase.

Although there are a number of cooling technologies that are used in various applications including mechanical vapour compression, vapour sorption, magnetic, acoustic and thermoelectric cooling devices. Almost all of these technologies use heavy and large parts like compressors or pumps to circulate the working fluids hence they pause risks associated with the use of moving parts and the leakage of working fluids. Currently, there is no available cooling technology to be used by MS patients that is: compact, light weight, portable, with no moving parts and circulating fluids and provide effective control for the cold surface temperature.

In this thesis, experimental studies were carried out to investigate the potential of using peltier cooling devices to develop an efficient, lightweight, compact and portable cooling device with no circulating fluids and no moving parts to be used by MS patients. This cooling device should be able to deliver cooling of the forearm to 18^{o}C for a period of 15 mins to achieve the required therapeutic effect as mentioned above. The first set of experiments was performed using a single peltier cooling device to find the best heat sink and to investigate the effect of using phase change material. The second set of experiments was performed using a multi peltier cooling module consisting of three peltiers and a PCM based heat sink to generate higher cooling effect. Cyclic operation was also investigated to study the performance of the cooling module under various conditions. From this study a number of conclusions can be made:

5.1 Single peltier experimental work

The single peltier was experimentally tested with six heat sink configurations including four heat sinks with various fin configurations; one heat sink with honeycomb and the sixth heat sink is with honeycomb and Phase Change Material (PCM). The tests were carried out at different power inputs of 0.5, 1, 1.5, 2, 3, 4 and 5 watts. Also, tests were carried with the PCM heat sink insulated and with a cover to simulate real operating conditions. The results of the first set of experiments with single peltier test facility showed:

1. The PCM based heat sink outperformed the other heat sinks configurations in terms of the achieved cooling temperature while maintain the heat sink at lower temperature levels. The PCM material served as heat storage medium where heat is stored as latent heat of melting thus allowing the temperature of the peltier hot side remaining relatively constant at low level.

2. Also, investigating the performance of the PCM based heat sink with insulation and lid to simulate real operating conditions where the cooling device may be covered with clothing showed that the peltier produced cooling below 12°C for about an hour at power input of 3 W.

5.2 Multi peltier cooling module experimental results

In the first set of experiments using the single peltier, the cooling load representing the hand was not included, therefore a second set of experiments with a multi peltier cooling module including three peltiers has been chosen to extract the heat from a hot body to represent the cooling load associated with the forearm. The peltiers were fitted with PCM based heat sink as concluded from above. Also, the forearm was represented by a water box. Experiments were carried out using various power inputs 3, 6 and 9 Watts and two PCM materials namely Paraffin Wax and OM37P. Also, experiments were carried out with different cycling scenarios. The results of this set of experiments illustrated that

1. OM37P phase change material produced a lower cooling temperature compared to paraffin wax where at power inputs of 3, 6 and 9Watts, OM37P produced cooling temperature of 15C, 11.6 and 15 compared to the Paraffin Wax that produced 20C, 18 and 18 respectively. Also, the cooling duration at these power inputs was 2000, 2000 and 1000 seconds with the OM37P where the cooling temperature remained below 15C while the Paraffin Wax was unable to achieve any cooling temperature below the 15C. Furthermore, the OM37P maintained relatively lower hot side temperature compared to the Paraffin wax particularly at low power inputs.

2. Results for the cooling load, coefficient of performance (COP) and heating load supplied to the PCM OM37P box at different power inputs showed that the highest COP of 0.56 at power input of 3W was achieved compared to 0.34 and 0.28 with power input of 6 and 9Watts respectively.

3. The results of the cyclic operation show that the device can operate in acyclic manner i.e. it can be switched on for 1800 seconds and then switched off for another 1800 seconds. With this cyclic operation, it is clear that starting from ambient temperature of 25C and 3 W power input, a cooling temperature of around 15°C was achieved throughout the first 1800 seconds. Switching off the peltiers for 1800 seconds proved not to be sufficient to regenerate the PCM material during the successive cyclic testing. Therefore to achieve the required performance, the device should be either switched off for a longer time or placed in a colder environment such as a refrigerator.

5.3 Overall analysis

Results have shown that this developed cooling technology can provide cooling to a temperature of 15C for a period of 30 minutes using power input of 3Watts, which will reduce the intension tremor for an MS patient for this duration. Also, according to the published medical research this will provide the MS patient another 30 minutes of continued tremor reduction post this cooling. Therefore in total, the MS patients can benefit from around one hour of reduced intension tremor by using this cooling device, which will have a major impact on their quality of life.

A major innovation in this technology is the use of PCM materials, which acts as a heat storage medium for the duration of use, therefore there is no need for an external cooling device (fan) to cool the peltier hot side, which makes the overall system more light and compact with no moving parts.

5.4 Future work

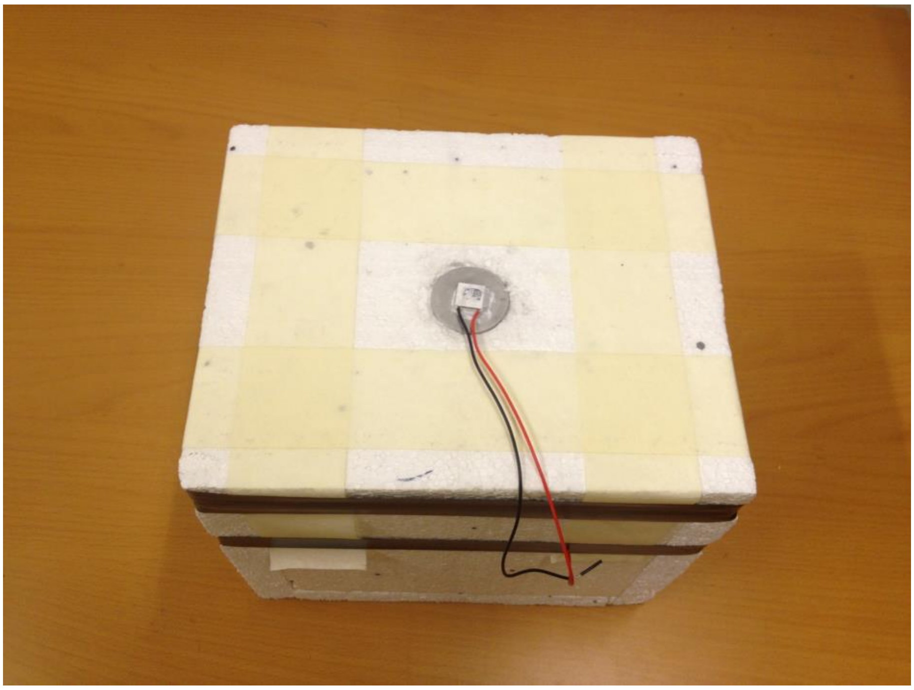
This research work has shown the potential of the developed cooling device for MS patients. To further the development of this device, the following future work is recommended:

1. A full scale prototype of forearm cooling device based on the modules developed in this research and laboratory tested to assess its overall power consumption, temperature distribution, mass and reliability. In this full-scale model, the human hand can be simulated with an element that characterizes the biological nature of human forearm where heat generation due to blood perfusion can be included.

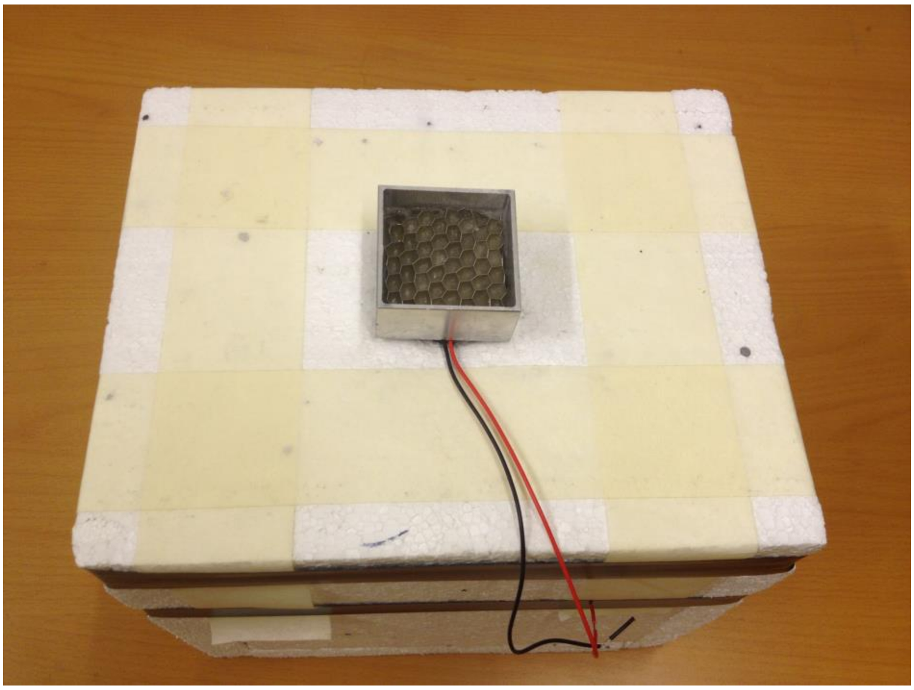
2. Using data from the above to develop a device that can be used on a real human forearm and carry out testing in a hospital environment.

6. Appendices

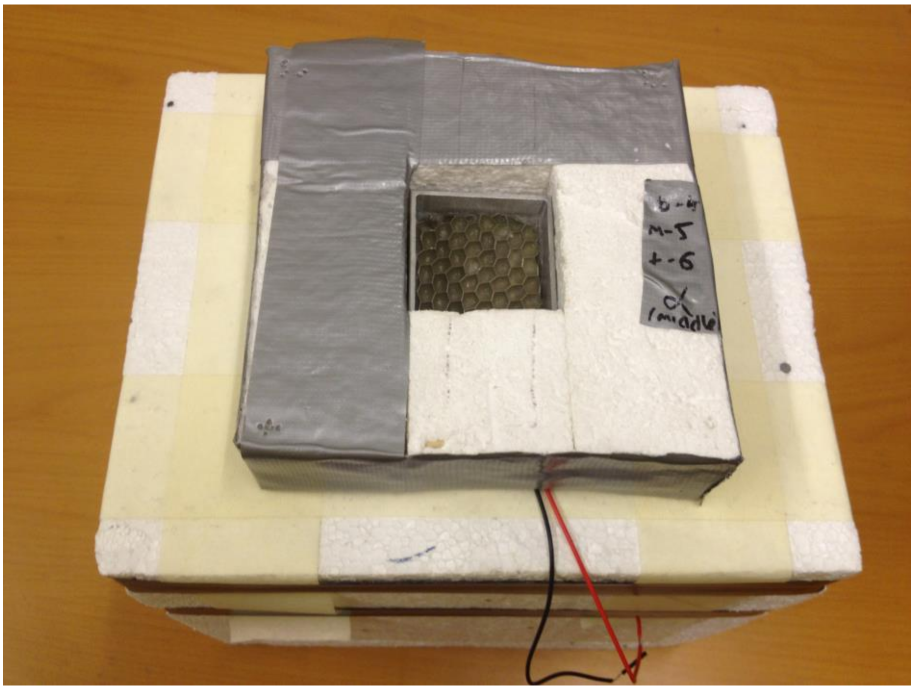
6.1. Single peltier test facility without heat sink



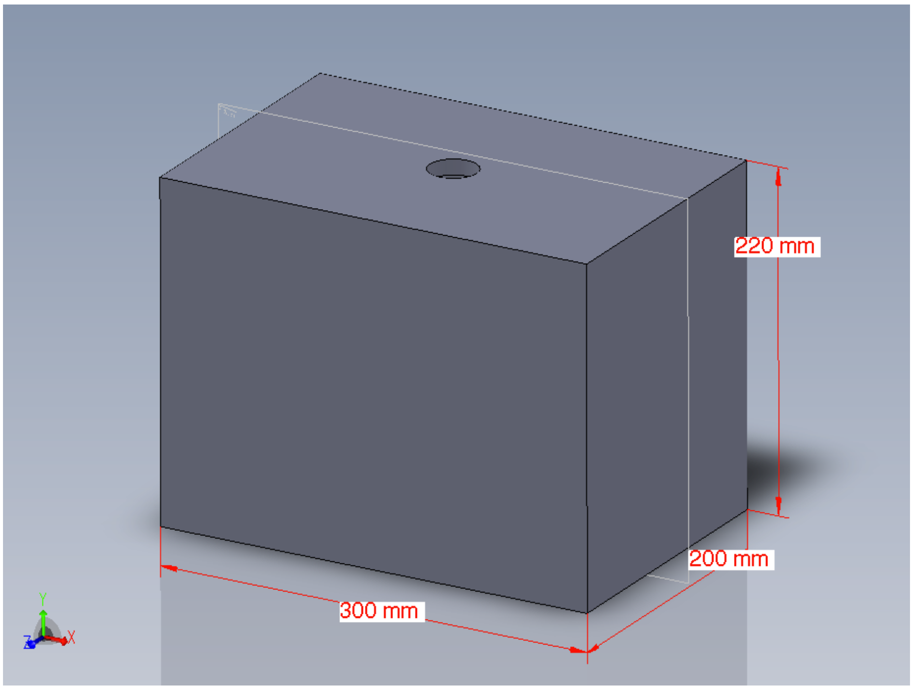
6.2. Single peltier test facility with the PCM heat sink on top of the peltier



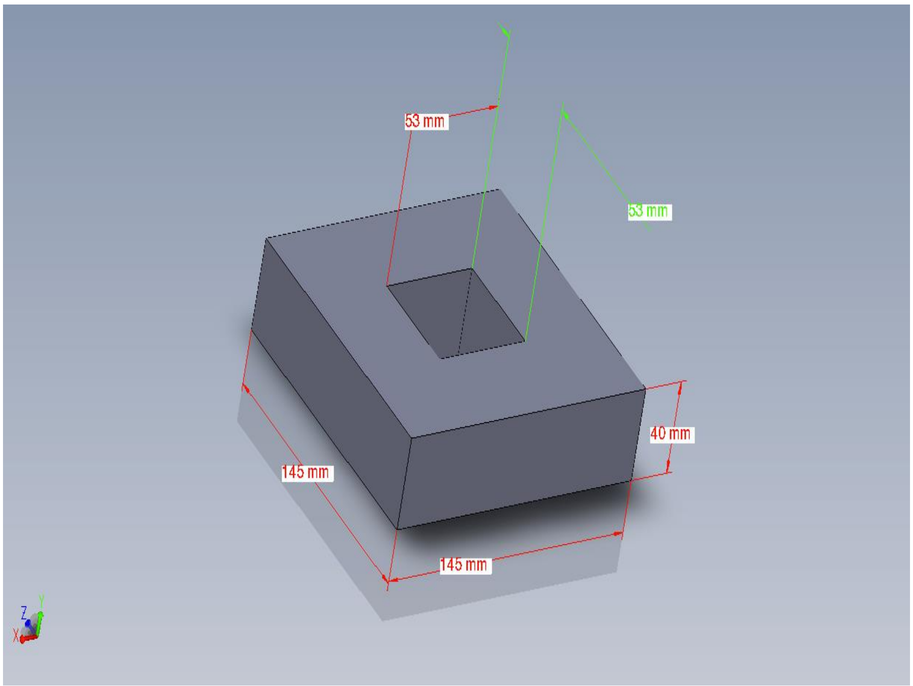
6.3. Single peltier test facility with the small insulating box around the HSU



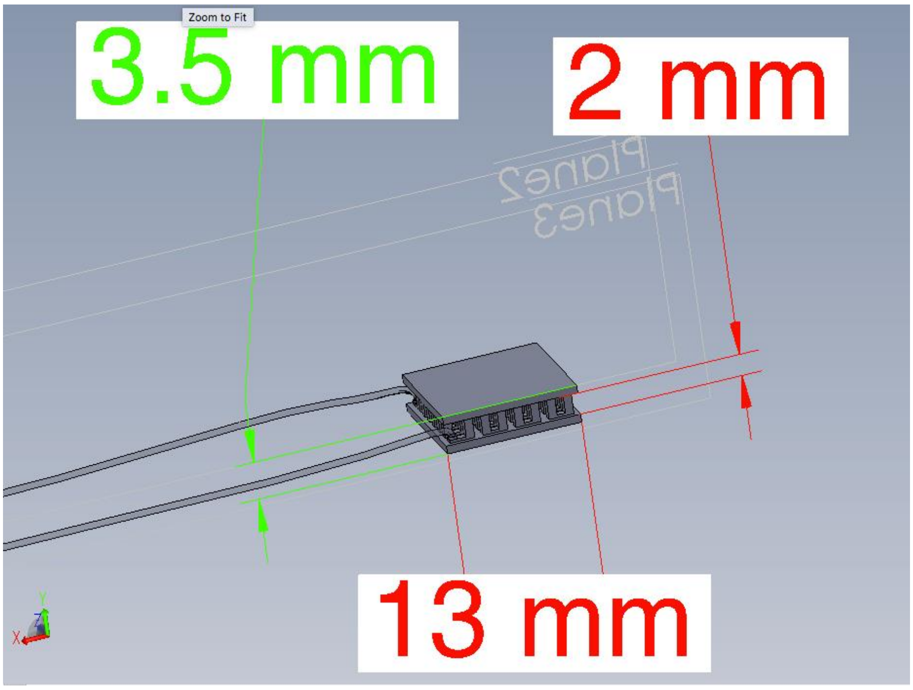
6.4 big insulating box



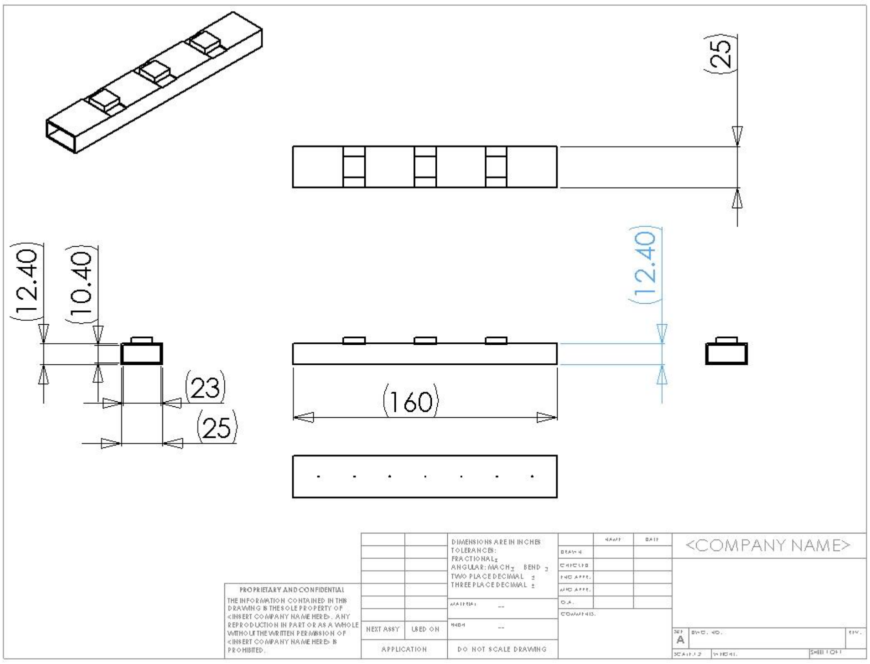
6.5 Small insulating box



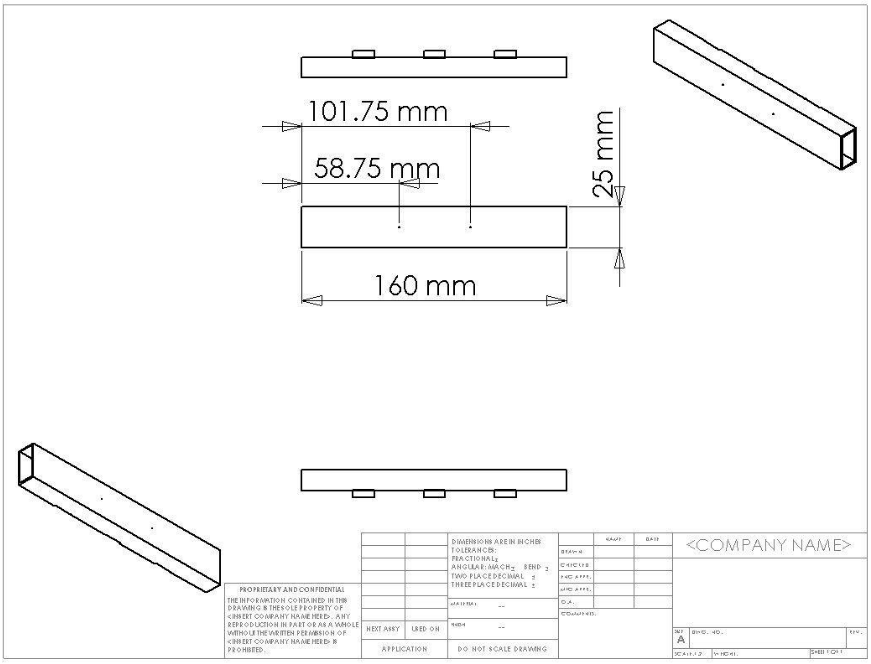
6.6 Peltier device



6.7 Front view of the PCM filled aluminium box



6.8 Bottom view of the water filled aluminium container



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