Phase change material for football helmet cooling system

by

Ramya Srinivasan

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Aerospace Engineering

Program of Study Committee:
Vinay Dayal, Major Professor
Hui Hu
Michael Dorneich

Iowa State University

Ames, Iowa

2021

DEDICATION

I would like to dedicate this thesis to my family. My loving parents, Thenmozhi and Srinivasan, deserve special thanks for their endless love, support, and encouragement throughout my life. My sisters, Divya and Saranya, have never left my side and deserve my wholehearted thanks.

TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

NOMENCLATURE

EHS	Exertional Heat Stroke
CNS	Central Nervous System
SBC	Selective Brain Cooling
PCM	Phase Change Material
TE	Thermo Electric
TPU	Thermo Plastic Urethane

ACKNOWLEDGMENTS

I would like to take this opportunity to express my gratitude to those who supported me in various aspects of this research. First and foremost, I would like to thank Dr. Vinay Dayal for his guidance, encouragement, patience, and unwavering support throughout the course of this research. I would also like to thank my committee members, Dr. Hui Hu and Dr. Michael Dorneich, for their support and encouragement.

I would like to extend my gratitude to my fellow graduate student and friend, Karthian Jadhav, for his contribution and cooperation in the research. In addition, I would also like to thank my friends, colleagues, the department faculty, and staff for making my time at Iowa State University a wonderful experience.

ABSTRACT

Football helmets worn during sports or high intense practices can aggravate the thermal load on the athletes, especially under sunny and humid weather conditions. Lack of heat dissipation can reduce their cognitive ability and resulting in loss of motor functions. Among athletes, football players are individuals most prone to heat-related deaths and illnesses during games and practices. Cricket players, who play extended innings, are also subjected to excessive heat related disabilities.

This work investigates the utilization of phase change materials in football helmets to maintain a comfortable head temperature for the athletes. The impact of solar radiation and wind speed on the cooling system were also examined. PCM pouch thicknesses have been analyzed for the optimization of heat flux values using Ansys Mechanical APDL software. The effect of pouch thickness on the cooling system was examined. The recharge time of the PCM to reuse them in helmets for cooling has been analyzed. The results indicate that the PCM cooling system can maintain a comfortable head temperature for up to 56 minutes. An optimum pouch thickness of 17 mm provides best cooling. The heat accumulated in the PCM pouch can be released by placing it in an ice box cooler for 15 minutes or placing it at room temperature for one hour to solidify it before reusing. Although the emphasis of this study is on the cooling of a football helmet, the results may be applied to the implementation of phase change material cooling solutions in several other products.

CHAPTER 1. INTRODUCTION

1.1 Heat Related Illnesses in Sports

Heat caused illness happens in almost every instance where there is prolonged intense activity. Exertional heatstroke (EHS) and heat exhaustion are most common in hot, humid climate, but they can also occur in cool weather, particularly during vigorous or prolonged exercise [1].

Hyperthermia refers to a category of heat-related disorders characterized by an abnormally high body temperature. It is a condition in which a person's body temperature increases above normal levels due to a lack in thermoregulation. In this condition, heat dissipated by an individual's body is much less than the heat produced or absorbed. It is also known as overheating [1, 34, 35].

Figure 1. Heat Exhaustion and Heat Stroke [45]

Exertional heat stroke is a serious medical condition defined as core temperature of more than 40° Celsius coupled with central nervous system (CNS) dysfunction [1, 37, 38]. Fatalities associated with EHS can be minimized with early detection and rapid cooling. EHS incidences have been observed for athletes more often during group running activities, American football, military combat training, road racing, and other activities requiring continuous, high-intensity exercise [1]. In contact sports like American Football, EHS has been initially misdiagnosed for concussion and it also has been mistaken for psychosis [1]. The symptoms and body temperature of Heat Exhaustion and Heat Stroke illnesses is shown in Figure 1.

Even though appropriate fluid consumption before and during training reduces dehydration and slows the rate at which core body temperature increases, hyperthermia can still occur with no substantial dehydration when a high intense training produces more metabolic heat than it is dissipated [1]. High intense sports activities like American Football, Soccer, Cycling, Running, and long duration workouts can cause hyperthermia or EHS to the athletes especially in hot environments [1]. It can cause the athletes to collapse and decrease their ability to concentrate on the game [1, 4].

1.2 American Football Uniform

Football players are some of the most vulnerable individuals to heat-related illnesses and deaths during games and practices. The football helmet and pads cover about half of the skin's surface area, while other clothing covers the remaining 20% [7]. As the Football uniforms and safety equipment worn during game (e.g., helmet, shoulder pads, gloves, knee pads, socks, turf shoes, clothing) covers most parts of the player’s body and has a thick padding, they build a microclimate above the skin surface that decreases heat dissipation to the atmosphere and greatly add to the heat load on a player [2, 7]. This microclimate can predispose an athlete to EHS or exercise-induced hyperthermia from a thermoregulatory standpoint.

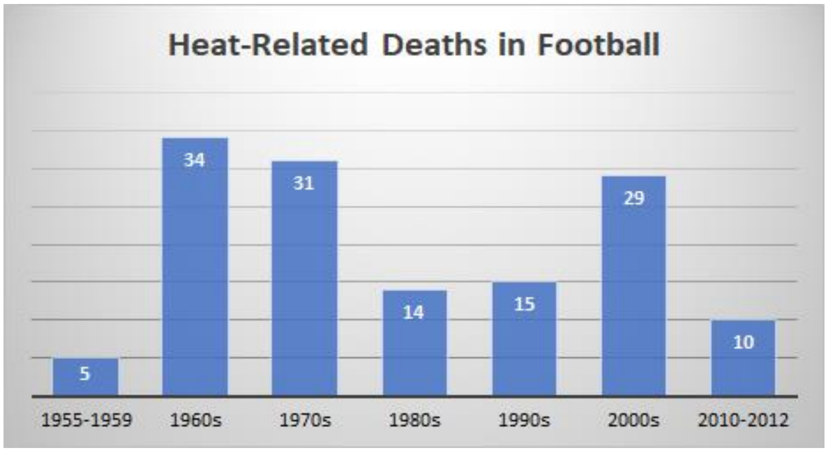

Figure 2. Heat related deaths in American Football [4]

There were 138 heat-related deaths recorded in the years between 1955 and 2012 in American Football that includes youth, high school, college, and professional athletes [4, 5]. On top of that, heat-related football deaths commonly affect young men who are perceived to be at the peak of health and physical fitness [4]. There were 52 football players (41 high school, 8 college, 2 professionals, and one sandlot) have died as a result of heat stroke since 1995 [5]. Heat related deaths in American Football from 1955 to 2012 is shown in Figure 2.

1.3 Heat Loss in Head

Heat loss must balance heat gain in order to achieve a stable body temperature. Rasch et al. [8], measured the heat loss from the human head during exercise and rest conditions under moderate to mild hyperthermia environmental conditions. According to their findings, the head surface has a massive heat sink capacity with a potential for heat loss greater than the heat generated by the brain. They also found that heat loss from the surface of the head was always greater than that from the respiratory tract and concluded that, during hyperthermia, the human head can serve as a heat sink with a heat loss potential that is greater than the heat generated by the brain and obtained from arterial blood.

The heat loss from the human head was measured by Froese and Burton [32] at nine distinct room temperatures ranging from - 2°C to 28°C. Their findings suggest that loss of heat from the head may account for a significant portion of overall heat loss of the body. They discovered that at extreme environmental conditions, half of a person's overall resting heat generation could be lost by heat loss from the head. The head plays an important role when it comes to thermoregulation as it has greater heat loss capacity due to its larger surface area [8, 9]. The head releases about 40-50 percent of the total heat generated in the body and thus, the head acts as a critical site for heat dissipation [8, 9].

1.4 Helmet Effects on Heat Loss

Rasch and Cabanac [3] conducted a study to measure the heat loss from head during exercise with and without wearing sports type headgear, and to determine if headgear inhibits Selective Brain Cooling (SBC) by reducing heat loss from the head. They created moderate hypothermia to the subjects through exercising and measured radiant heat loss, convective heat loss, local evaporative heat loss, and head skin temperatures. They concluded that wearing headgear limits head heat loss, minimizing head cooling and SBC effectiveness.

Brothers [2], investigated whether a football helmet worn during vigorous workout can cause a substantial rise in core temperature as expressed by esophageal temperature, head skin temperature, and heart rate. They found that wearing a helmet substantially increases these factors especially in sunny and high humid weather conditions and greatly affects the heat dissipating mechanisms on the head. Their results show that during increased exercise intensity and time period, metabolically generated heat produced in the body overpowers the body's thermoregulation systems that serve to dissipate the heat generated.

Therefore, wearing a helmet in sports or other areas of work such as the army and firefighters, can restrict one's ability to dissipate heat optimally, and hence aggravates thermal load on the athletes, especially under warm environmental conditions [2, 3]. Helmet cooling is therefore essential to provide overall thermal comfort for the players and can be helpful in reducing heat-related illnesses and deaths in football.

1.5 Cooling Systems

There are different cooling techniques that are being investigated to provide necessary thermal comfort while using the helmets. Some of them include thermo-electric cooling [10, 11], air-conditioned helmet cooling system [12, 39], a ventilation system [13], Solar power operated cooling system [14].

Buist and Streitwieser [10] designed a Thermo-electric (TE) cooled helmet system for motorcycle and race car helmet types. The top interior of their helmet is covered by a cushion filled with thermo-electric cooled liquid. Their cooling system consists of a flexible braided wire located inside the liquid cushion to collect the heat, a 12-volt TE module to extract heat from the cushion, and a heat sink finned aluminum radiator to exhaust heat to the atmosphere.

Cao et al. [11] proposed a new cooling helmet that is cooled using TE refrigeration and a mix of air and water cooling, allowing the head and neck to be cooled at the same time. Their cooling system consists of two sets of TE cooler, radiator, micro-fan, one air-cooler and a liquid-cooler. In their air-cooling refrigeration module, the air is transported to the air cooler, where it is cooled by micro-fans before flowing into the helmet to keep the head cooler. A micro pump circulates the liquid cooled by the second TE cooler into the liquid cooling tube to remove the heat from the neck.

Another TE air-conditioning system for crash helmets was proposed by Goldsborough [39] in 2004. It includes a blower fan located at the back of the helmet which acts as an air intake passage to draw air from the back region and force them into the front region of the helmet. In the interior of the helmet, a thermoelectric cooling element that is powered by a DC power source is connected to the intake passage downstream of the blower fan. There is an external heat sink on the outside of the helmet. The air that passes over the TE cooling component cools and conditions the helmet's head.

Pierce [13] proposed a ventilation system for helmets that enables the interior of the helmet to be ventilated. It provides ventilation for the helmet's cheek bar area and can include ribbed passageways that facilitate airflow in the helmet's interior, as well as access openings in an intermediate section that couples the airflow from the ribbed passageways to the airflow from the access openings.

A solar power operated helmet cooling system has been proposed by Jwo and Chien [14] in 2005. It consists of a flat solar cell panel positioned on the helmet's top wall for transforming solar energy into electric energy, which drives a TE cooling module and a mini fan-based cold air distribution unit to maintain the interior of the helmet body cool.

A battery-operated fan or blower installed in the dome of the helmet that provides conditioned air, either cooling or heating, was developed by Waters [12]. It guides the air flow between the fan and the wearer's head, over a temperature control panel of coolant or heat source, forcing the air downwardly over the wearer's head, neck, and shoulders.

1.6 Drawbacks of Cooling Systems

Generally, for these cooling systems, there are advantages and disadvantages associated with them. For instance, to enable the thermoelectric cooling system, external power sources are required. When installing a fan and motor assembly or a TE cooler in a helmet, the power supply arrangement and mounting space in the helmet frame must be addressed, as they can compromise the helmet's structural integrity. In traditional designs, the fan and motor assembly or thermoelectric cooler are driven by the motorcycle battery or a storage battery. These traditional designs are also unsatisfactory in terms of functionality. Installation and maintenance of these cooling systems may require additional efforts. Some designs may require significant adjustments that can affect the structural strength of the helmet. Moreover, it is important to consider the additional costs associated with the implementation of these solutions. The noise and vibrations generated by the fan will be another aspect which will make the wearer uncomfortable after prolonged exposure.

The use of phase change material (PCM), which has a high latent heat of melting, is a simple alternative solution to the problems associated with these cooling systems. This work presents a novel method of helmet cooling. The passive nature of a PCM, which does not require any external energy source, is soundless and does not significantly increase the weight of the helmet.

CHAPTER 2. PHASE CHANGE MATERIALS

2.1 Phase Change Materials Definition

"A Phase Change Material (PCM) is a substance with a high latent heat, capable of storing and releasing vast quantities of energy when melted and solidified at a specific temperature" [26]. PCM provides useful cooling by absorbing sufficient heat at relatively constant temperature using phase transition [20, 21]. It can be switched repeatedly between the crystalline and amorphous phases [22]. Phase transition of PCM is represented in Figure 3. Helmet cooling with PCM is widely considered as an inexpensive, compact, reliable and simple solution to implement [15, 16, 17, 18, 19].

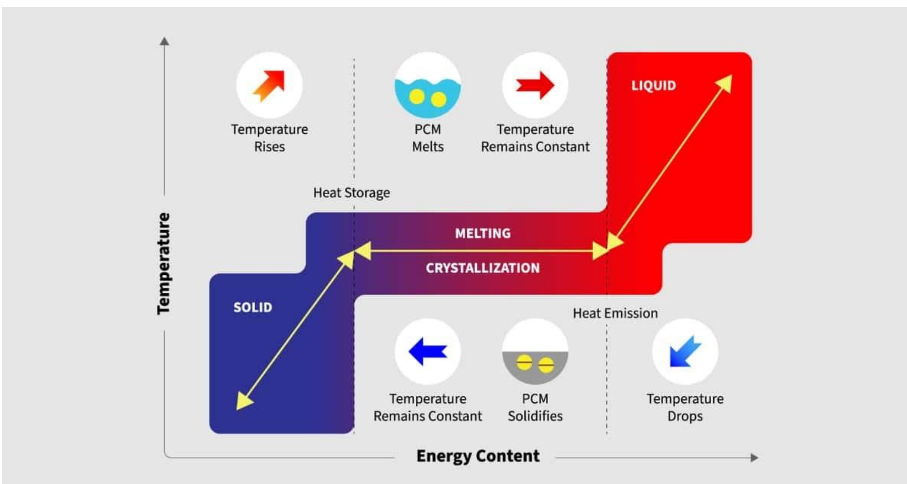

Figure 3. PCM Phase Transition [26]

2.2 Classification of PCM

There are several types of PCMs including Paraffins [15,16, 17, 27], Hydrated salts [28], Dry PCM [30] can be used. Paraffin based PCMs are comparatively inexpensive and easily available. They have greater heat storage capacity and are non-corrosive [29]. The liquid phase of the Paraffin PCM, however, causes problems with the containment of the fluid that may result in increased complexity and expense [15].

Hydrated salts are appealing substances that can be used in heat storage applications because of their large volumetric storage density, comparatively high thermal conductivity, and lower costs than paraffins [30, 40]. However, they have corrosive properties that affect the design of PCM storage units by limiting the material used or requiring surface coatings on the material [29].

Dry PCMs include microencapsulated composite materials and solid-solid organic materials [30]. Microencapsulated phase change composites, in the form of a powder, are made up of tiny beads that contain PCM inside thin polymer shells. The individual capsules have a diameter ranging from ten microns to one millimeter and have impermeable, semi-rigid walls that are usually less than one micron thick. The geometry of Microencapsulated PCM is shown in Figure 4. “Solid-solid organic materials undergo reversible solid state crystal structure transitions at temperatures ranging from room temperature to about 100°C” [30]. These materials have large transition heats that are equal to, if not better than, paraffin based PCMs. Dry PCMs help to avoid liquid containment problems and simplify the design of PCM storage units.

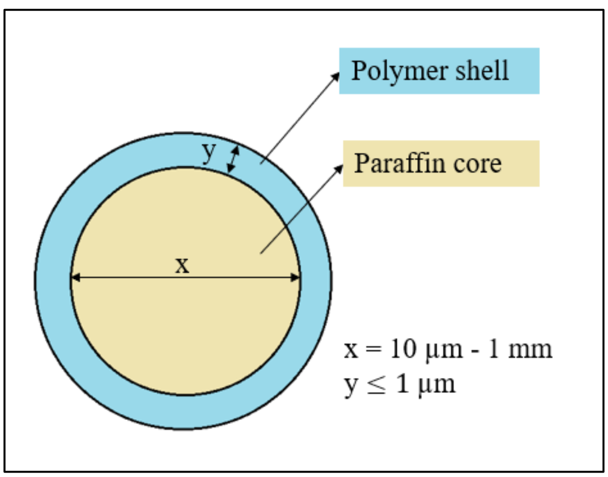

Figure 4. Microencapsulated PCM

2.3 Various Applications of PCM

In today's world, PCM has a broad range of applications. The ability of PCMs to store heat energy can be used in a variety of ways to improve human comfort. PCMs are incorporated into building walls and components such as paints, wallboard, plaster, glass windows, shades, heat and cold storage units to maintain optimum room temperature. It helps in the reduction of the air conditioning unit's size and helps to solve the overheating or cooling issues [26].

PCMs are used in solar water heater systems. A layer of PCM is filled at the bottom of a built-in storage-type water heater. When the sun shines, the water heats up and passes heat to the PCM and the PCM starts melting as it absorbs energy. During the hours when the sun is not shining, the hot water is turned off and replaced with cold water that gets its energy from the PCM. The PCM releases energy as it transitions from liquid to solid state [26].

Phase change materials are used in textile applications including clothes, blankets, insulation, boots, protective clothing, military uniforms [27], and many more, to maintain a comfortable human skin temperature during hot or cold environments. PCM is being incorporated in spacesuits to maintain a comfortable temperature for astronauts in space [49]. The results from a research [27] conducted to assess the effectiveness of phase change materials-based personal body microclimate cooling systems and their impact on a soldier's physiological stress in the course of exertional heat stress in a sunny weather, proved that the cooling vest made of PCM placed over the military uniform was able to minimize physiological pressure during trainings.

PCM could be embedded into fibers or polymers, or it could be deposited on fabrics in the shape of microcapsules to maintain and release heat energy from the body as needed [26]. PCMs are widely used in the medical field for multiple purposes. They are used to maintain the temperature range of vaccines by integrating them into vaccine containers and therefore helps to increase the lifetime of vaccines. They are used for transportation of vaccines, blood, and several other items with temperature sensitivity [26].

There are currently gel pads containing PCM that are available for treating damaged joints or limbs. PCM helps in enhancing the gel pad's thermal energy storage ability. The PCM incorporated pad can be encapsulated, pelletized, soluble, insoluble, or any other desired shape. Cushions, rolls, and other medical therapy items have also been produced using a bound PCM in an extremely fine shape. The PCM substance is nontoxic and extremely comfortable [26].

2.4 PCM Cooled Helmet Systems

Installing PCM within a helmet can help to efficiently preserve heat discharged from the head as it transitions from solid to liquid form. As this phase transition happens at a steady melting temperature, it is possible to maintain a comfortable internal helmet temperature till the PCM is fully melted. The phase change takes place noiseless and with no extra energy input or extraction.

Tan and Fok [15] investigated the development of a helmet cooling system that uses PCM to collect and preserve the heat generated from the head of the wearer in order to provide comfortable head temperature for the wearer. They placed the PCM between the interior of the helmet and the head of the wearer through a pouch and by conduction, heat from the wearer's head is transmitted to the PCM through a heat collector that is distributed around the wearer's head. They used basic calculations with thermal resistance networks and demonstrated that their suggested PCM-cooled motorcycle helmet concept can be integrated into a conventional helmet to achieve head cooling for up to 2 hours without the requirement of a battery or electricity.

The novel application of innovative fabrics containing paraffin based PCMs in the development of a barrier layer between the head and padding of a motorcycle helmet to regulate the heat within the helmet was investigated in a study conducted by Sinnappoo et al. [41]. They used various PCM coated textile materials and used them as liner inside the motorcycle helmet and a hood with interchangeable paraffinic PCM inserts was part of the fabricated cloth liner. They found that by using PCM substances as a cloth liner, it is possible to decrease the temperature inside the helmet by 3.8° Celsius.

A study by Ghani at al. [17] investigated the use of forced convection and PCM to monitor the thermal comfort of helmet users. They evaluated the effects of solar radiation, forced convection, and PCM integration on the thermal performance of an industrial helmet. They found that PCM incorporated in the helmet helps to extend the duration of thermal comfort for the wearer. Their findings also revealed that the heat generated by the head is the most important factor that affects the PCM melting time.

The usage of a PCM cooled system for a motorcycle helmet has been investigated by Fok, Tan and Sua [16]. They also conducted experiments on the effect of solar radiation, wind speed, and rate of heat generation on the PCM melting time. Their findings also demonstrate that a phase change material cooled helmet will extend the thermal comfort time in comparison to a standard helmet.

Many researchers have investigated the effectiveness of using PCM cooling techniques for motorcycle helmets, safety, and construction helmets [15, 16, 17, 18, 19]. But there is not much literature on using PCM cooling techniques for football helmets. This paper aims to experimentally evaluate the effectiveness of a composite football helmet cooling system using Phase Change Material (PCM).

CHAPTER 3. EXPERIMENTAL DETAILS

3.1 PCM Selection

In order to achieve comfortable head temperature while wearing a helmet, it is crucial to select the right PCM substance. The melting temperature of the PCMs should be determined based on the applications. The PCM starts to melt to provide a cooling effect on the head when the temperature of the head is more than 30°C. The PCM pouch has a warming effect when the skin temperature is below 30°C.

The PCM, Nextek 28D-SP, which has a melting temperature of 28°C, is selected for this work. Nextek 28D is a dry powder, microencapsulated material. It has an acrylic polymer shell and a paraffin core material. The phase change of the PCM takes place inside of the microcapsule (MF Polymer wall). The capsule wall acts as containment for the PCM as it melts and freezes and hence it eliminates liquid containment problem and has higher thermal conductivity. It could be compared to the composition of an M&M which has a candy coating on the outside, chocolate in the middle. So, the capsule itself stays solid the entire time (for all the microencapsulated materials) and the melting and freezing of the PCM is occurring inside of the capsule. This PCM is non-toxic, inexpensive, and easily obtainable in the market. Currently, the cost per pound is about $5. The properties of Nextek 28D PCM are shown in Table 1.

Table 1. Properties of PCM Nextek 28D-SP

Description	**Value**
Melting Temperature	28°C (± 2°C)
Freezing Temperature	21°C - 23°C
Thermal Conductivity	0.8 W/m.K

Table 1. Continued

Density (Bulk density of capsules)	~ 0.555 g/ml
Specific Heat	2.1490 J/g - °C
Heat of Fusion (Latent Heat)	≥ 155 J/g
Appearance	White to slightly off-white color
Form	Dry Powder (≥ 97% solids)
Particle size (average)	15-30 micron

3.2 Design of PCM Cooled Football Helmet

PCM pouch is made of thin and flexible copper sheet of thickness 0.172 mm. Copper has high thermal conductivity and provides efficient heat transfer between head and PCM through the thin foil. Copper sheets are soldered together in order to store PCM inside it. The dimension of the pouch used in this work is 132 x 114 x 13 mm. The pouch thickness is small, so that the primary safety requirement of the helmet would not be compromised by the installation of the PCM pouch into the helmet. Pouch includes an aluminum honeycomb core and is filled with 30 grams of PCM Nextek 28D. PCM pouch is attached to the interior of the helmet using a Velcro tape. Schutt Vengeance A3 Youth Football Helmet is used for this research. Figure 5 Shows the exploded view of the PCM pouch and Figure 6 shows the design of PCM cooled football helmet.

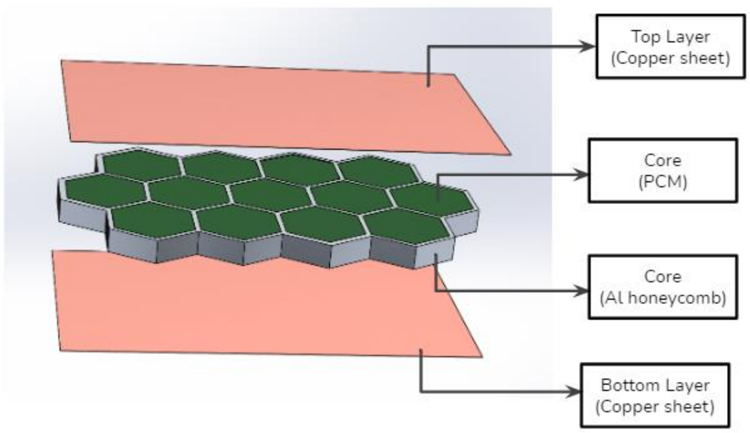

Figure 5. Exploded view of PCM pouch

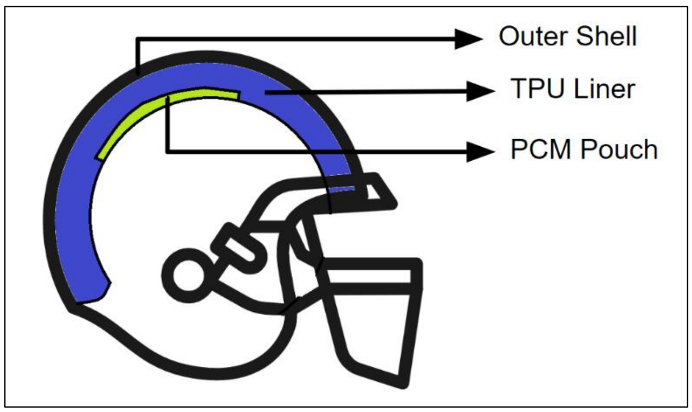

Figure 6. Diagram of PCM cooled football helmet

In general, PCM has a very low thermal conductivity that would lead to a low rate of heat transfer. Therefore, it is necessary to enhance their thermal conductivity in order to achieve good cooling performance. Padmanabhan and Murthy [25] investigated the usage of fins in PCM to enhance the heat transfer rate and stated that using thin fins made of good thermal conductors is one way to increase the heat transfer for energy storage applications. Fok et al. [23] also recommended that the PCM heat transfer process could be enhanced by the internal fins. To achieve efficient heat transfer, a thin wire mesh or honeycomb framework within the PCM pouch could be used. An aluminum honeycomb core is installed inside the PCM pouch for this purpose. Aluminum has high heat conductivity and good heat transfer properties. Honeycomb sandwich structures have a high strength-to-weight ratio, as well as outstanding crush resistance and energy absorption capacity, which can minimize force of impact even further during collisions [24].

3.3 Experimental Set-up and Testing

The research involved testing the cooling performance of a football helmet installed with Phase Change Material cooling system. The diagram of the experimental setup is shown in Figure 7. Football helmet installed with PCM cooling system is securely placed on the testing platform. The heat produced from the top of the head is simulated in our experiment using a 10W silicone heater (Silicone Rubber Heater from Phoenix Thermal Supply). Froese and Burton [32] examined the sensible heat loss from the human head using a gradient calorimeter and found that sensible heat loss at ambient 25°C is 14W. Clark and Toy [31] studied forced convective heat transfer distributions around the human head and observed that heat lost from head is about 10W at 23°C atmospheric temperature.

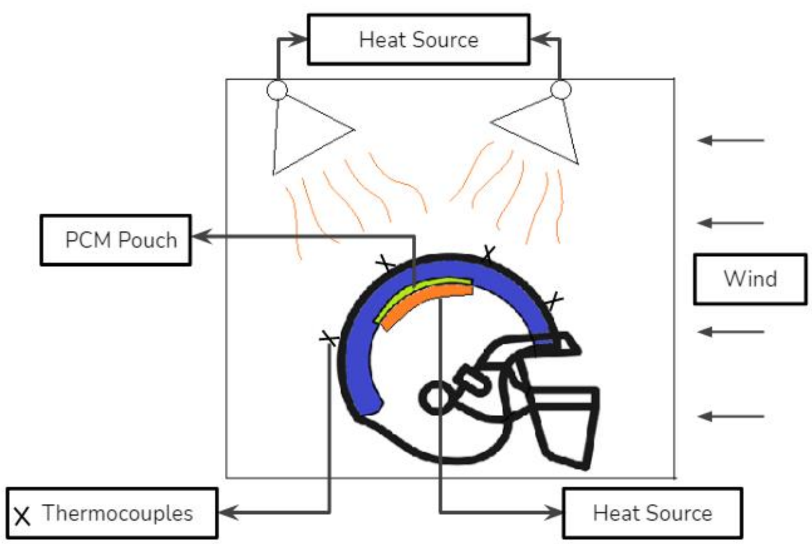

Figure 7. Experimental setup

A digital temperature controller is used to record the desired head temperature for the heater, and it displays the heater temperature variations. The heater is set to a maximum temperature of 42°C. The average normal body temperature is 37°C [35, 36, 37]. Hyperthermia, or EHS occurs during exercise or athletic activity when the body temperature reaches 40°C and above [33, 34, 35].

Solar radiation is simulated using four heat radiators (250W Ceramic Heat Radiators) mounted at an angle of 45° downstream using a heat lamp fixture as shown in the figure. The radiator is positioned at a distance from the helmet where the heat can increase the helmet outer surface temperature from 28°C to 60°C in 15 minutes in a windless environment. A standing fan is used to simulate wind conditions in the football field, and it is set to a speed of 4.2 m/s. It is kept at a distance of 30 cm from the helmet to simulate the average speed of football players which is around 5 m/s [47]. Wind velocity of the fan is measured using a cobra probe anemometer. Temperature on the helmet outer surface, PCM, and PCM pouch are all measured using ten K-type thermocouples. Four thermocouples are positioned on the helmet outer surface, three thermocouples are positioned on the PCM pouch and three more are inserted into the PCM pouch to find the PCM temperature. All thermocouples are connected to a digital multimeter from which the temperatures are captured.

An empty copper pouch without PCM was mounted into another identical football helmet for the purpose of comparison. The weight difference between PCM cooled helmet and the regular helmet is 84 grams. Table 2 shows the weight distribution of the PCM cooled football helmet. The pouch increases the helmet weight by 6.3%.

Table 2. Weight distribution of the PCM cooled football helmet

Product Description	**Weight (in grams)**
Regular Football Helmet (without PCM pouch)	1323
Copper Pouch	54
Al Honeycomb	1
PCM	30
PCM Pouch (Copper pouch + Al Honeycomb + PCM)	84
PCM Cooled Football Helmet	1407

CHAPTER 4. RESULTS AND DISCUSSION

4.1 Impact of PCM on the Internal Temperature of Helmet

A heater power of 10W is applied under radiator heat and no wind conditions. The heater input temperature and the helmet interior temperature, after applying 10W heater power, is shown in Figure 8. This shows that on an average there is 1.6°C difference from the heater to the helmet, and the trendlines are linear. The standard deviation of the heater fluctuations is also shown in the graph (Figure 8). The resolution of the type K thermocouple used in the work is 0.1°C. The thermocouple temperature is recorded from the digital multimeter at an interval of 1 minute till the pouch reaches hyperthermic temperature of 40°C.

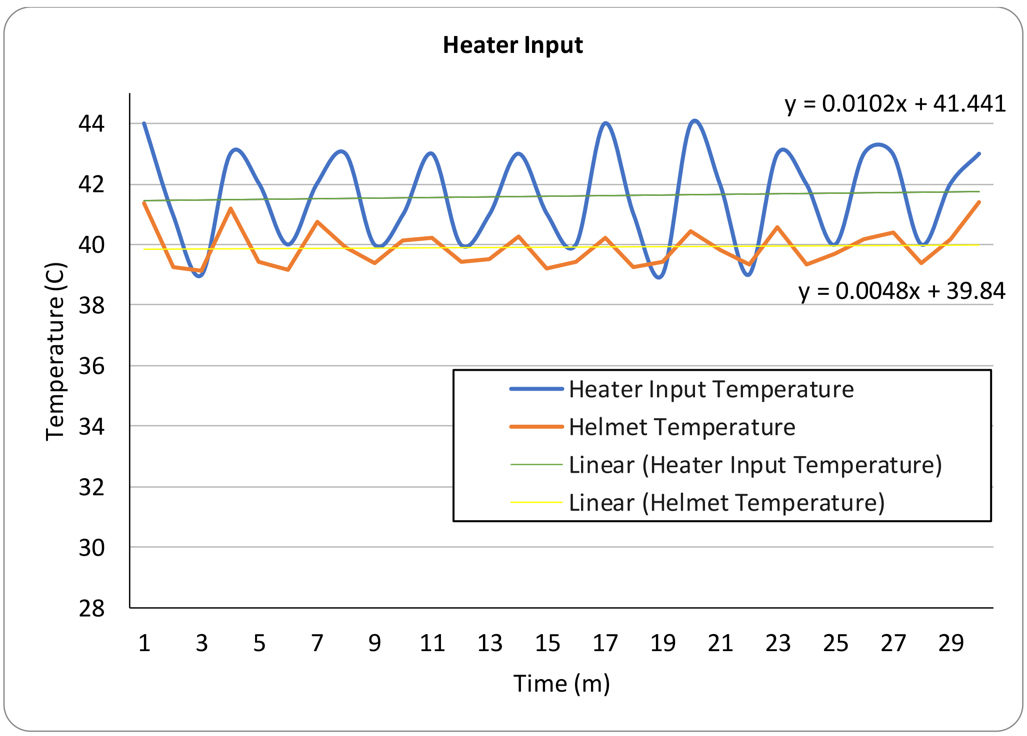

Figure 8. Heater Input Temperature

PCM pouch temperature versus time interval are compared for regular and PCM-cooled football helmets in Figure 9. The regular helmet (without PCM) took about 11 minutes to reach 40°C whereas the time increase to about 56 minutes for the PCM cooled helmets. The results indicate that by using PCM, the temperature inside the helmet can be maintained at an average body temperature of 36°C [35, 36, 37] for a prolonged period of time. Thus, PCM-cooled helmets prevent the head from reaching hyperthermia, and EHS temperature of 40°C [33, 34, 35] for up to 56 minutes.

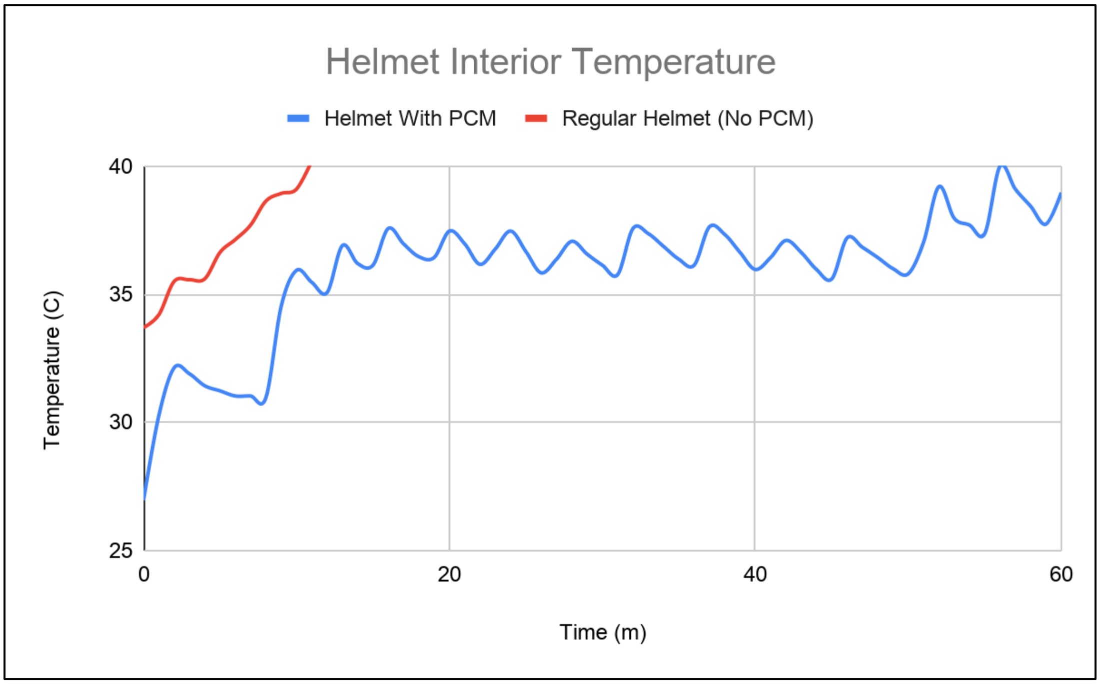

Figure 9. PCM Pouch Temperature vs Time - Regular and PCM cooled Helmet

4.2 Impact of Wind on the Internal Temperature of Helmet

PCM pouch temperature versus time interval of PCM-cooled football helmet is compared for wind and no wind conditions in Figure 10. A heater power of 10W and simulated solar radiation heat was applied during the testing. The tests were carried out in an adiabatic setting, with an insulation covering (polystyrene foam) around the heater, in order to reduce heat transfer from the heater to the environment. During no wind conditions, the internal temperature of the helmet reached 40°C in 56 mins whereas a wind speed of 4.2 m/s seems to prolong this time to up to 85 minutes. The wind speed does have a substantial impact on the interior helmet temperature, and this could be attributed to this helmet's design which includes three vent holes on the helmet exterior surface and a breathable TPU enhanced liner instead of a traditional foam liner.

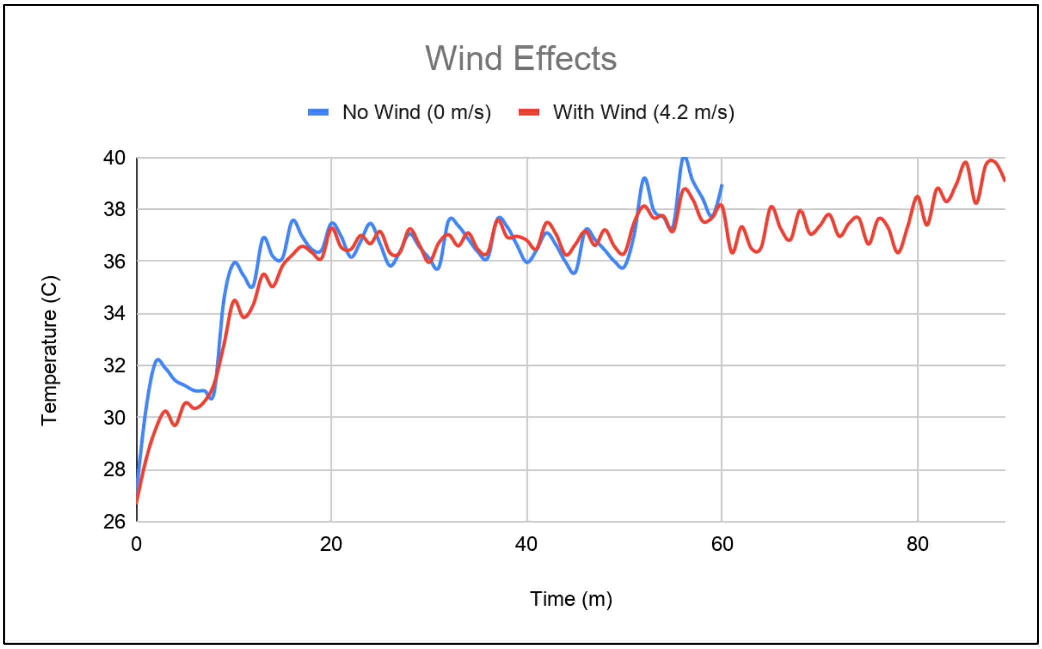

Figure 10. PCM Pouch Temperature vs Time – With and without wind

4.3 Impact of Solar Radiation on the Internal Temperature of Helmet

PCM pouch temperature versus time interval of PCM-cooled football helmet is compared for with and without artificial solar radiation in Figure 11. The helmet is subjected to a heater of power 10W under no wind condition. During the absence of simulated solar radiation, the internal temperature of the helmet reached 40°C in 78 mins whereas with solar radiation the time decreased to 56 minutes. Our results show that helmet interior temperature is higher during simulated solar radiation conditions and therefore it indicates that the external environmental conditions have a significant influence on the internal temperature of the helmet.

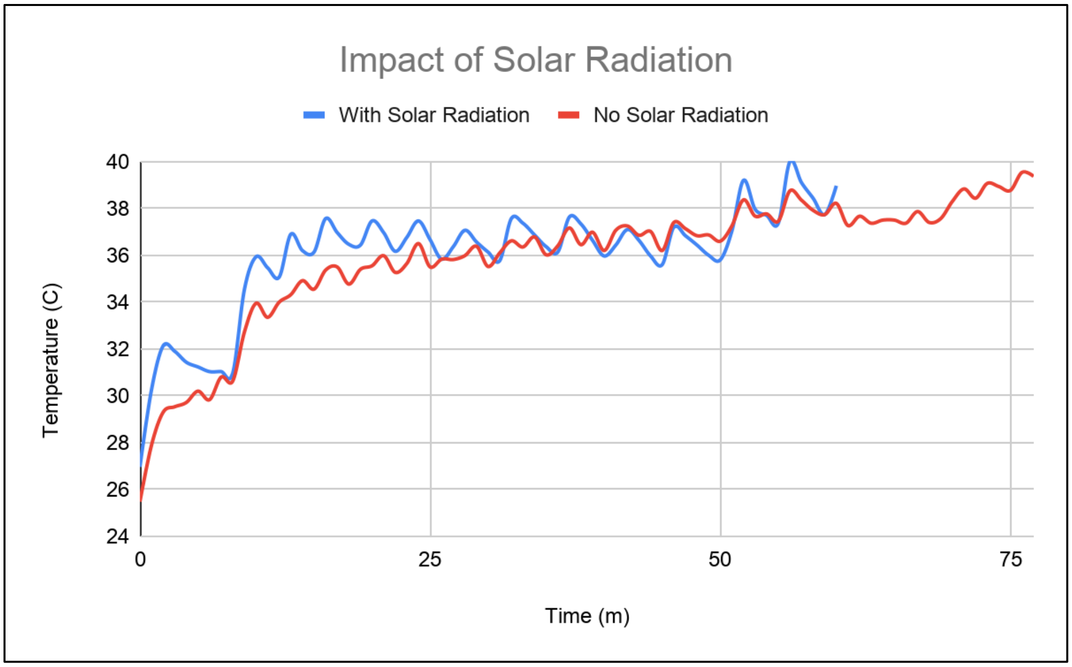

Figure 11. PCM Pouch Temperature vs Time – With and without solar radiation

4.4 Impact of Pouch Thickness on Helmet Cooling System

A single cell of Aluminum honeycomb along with the PCM, copper sheets and the helmet layers including the TPU inner liner and polycarbonate outer shell has been designed and analyzed on Ansys Mechanical APDL software to find the heat flux rate for various pouch thicknesses. Ansys model along with its materials is shown in Figure 12. “Heat flux (W/m^2) is the rate of thermal energy flow per unit surface area of heat transfer surface” [48]. Average heat flux (W/m^2) results are plotted against different pouch thickness (mm) values in Figure 13. Our results indicate that highest heat flux results are obtained for a pouch thickness of 17 mm, and it starts decreasing after that value.

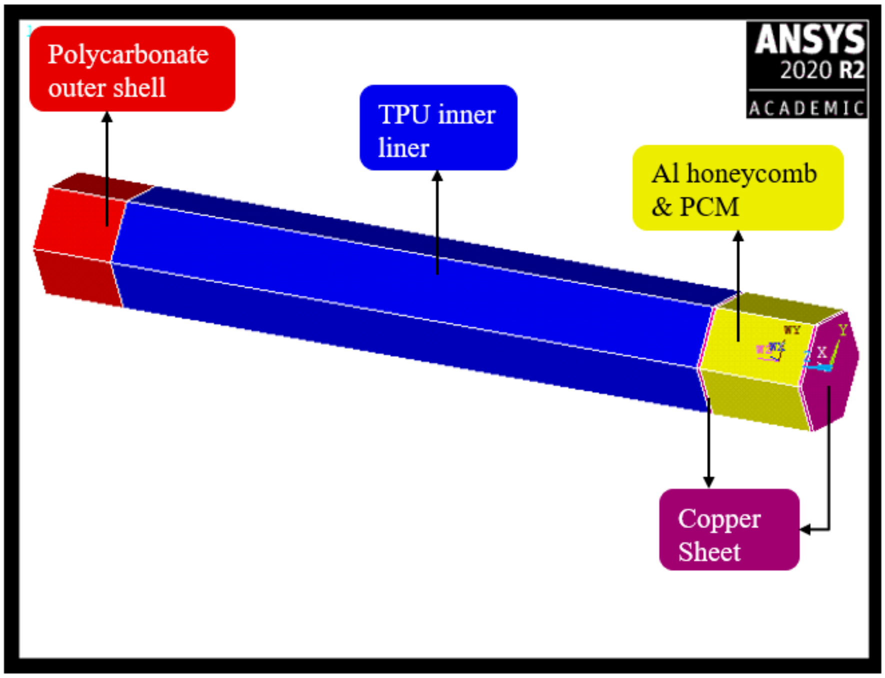

Figure 12. Ansys model for pouch thickness analysis

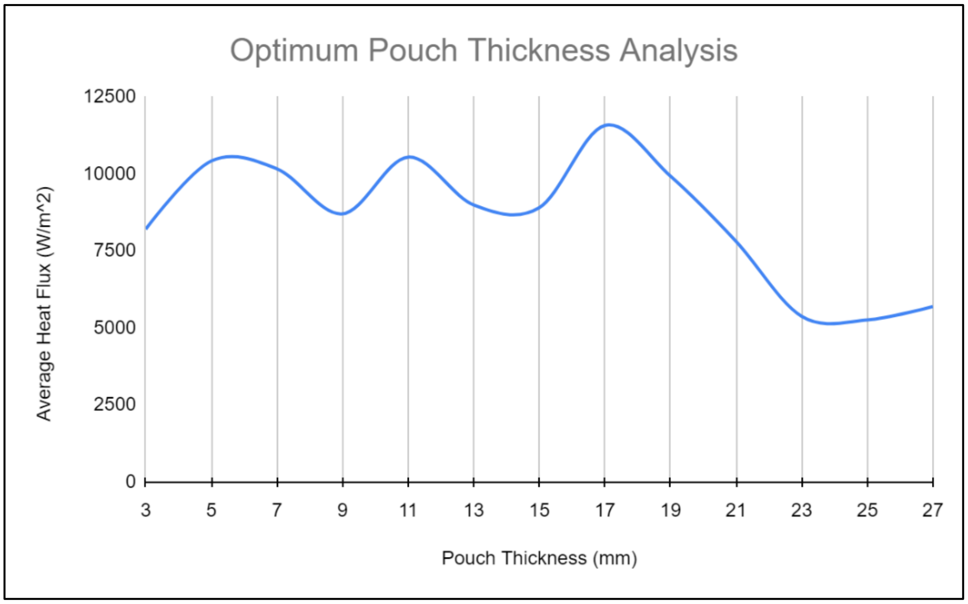

Figure 13. PCM Pouch Thickness vs Average Heat Flux Results

In Figure 14, PCM pouch temperature versus time interval are compared for two different pouch thickness of PCM-cooled football helmets. Optimum pouch thickness result 17 mm obtained from the Ansys thickness analysis is compared with 13 mm thick PCM pouch. A heater power of 10W and simulated solar radiation heat was applied during the testing under no wind conditions. The results indicate that by using a PCM pouch of 13 mm thickness, the temperature inside the helmet can be maintained at an average body temperature of 36°C for up to 56 minutes whereas by using optimum pouch thickness of 17 mm, the helmet interior temperature can be cooled at an average of 34.5°C for up to 80 minutes. Therefore, prolonged period of cooling time and more efficient cooling temperature could be achieved by using 17 mm optimum thickness of PCM pouch.

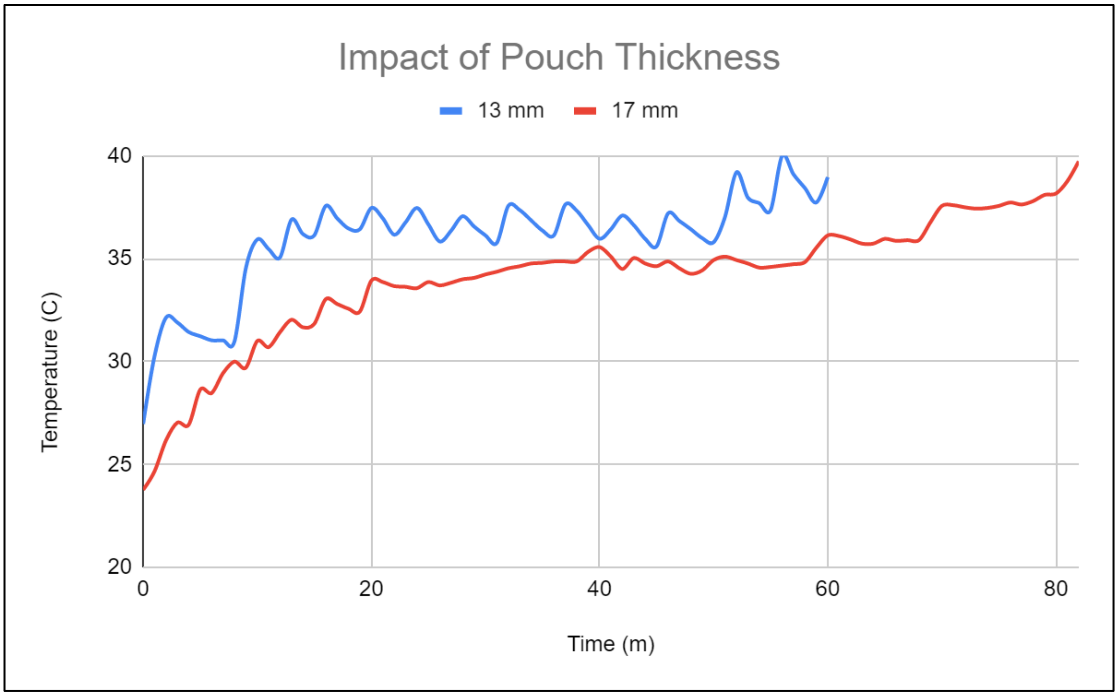

Figure 14. PCM Pouch Temperature vs Time – 13 mm and 17 mm Thickness

4.5 PCM Recharge Time

Heat energy stored in PCM could be discharged by keeping them below their melting temperature. PCM pouch could be easily removed from the helmet as it is attached only using a Velcro tape. Two experiments were conducted to estimate the recharge time of PCM pouch for reusing once it has been heated. In the first experiment, the PCM pouch was enclosed within a zip lock bag and kept in a portable ice box cooler that is made of polystyrene foam and filled with ice cubes of average temperature -4°C. PCM temperature was monitored with 4 thermocouples and within 15 minutes the PCM reached its freezing temperature of 21°C.

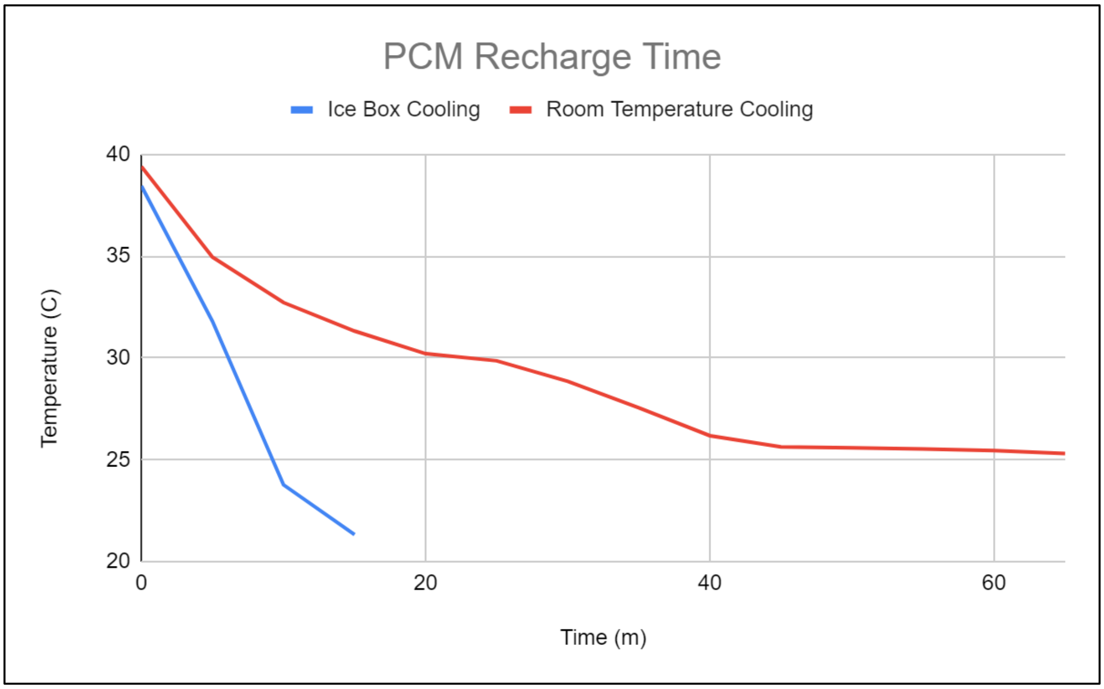

Figure 15. PCM Pouch Temperature vs Time – Ice box and Room temperature cooling

In the second experiment, the PCM pouch was kept at room temperature of 22°C and PCM temperature was monitored using 4 thermocouples. It took up to one hour for the PCM to reach below its melting temperature (28°C). PCM Nextek 28D is typically solid at room temperature. This shows that using a Styrofoam ice box cooler helps in expediting the recharge time of PCM. Once the PCM is recharged (heat discharged to ambient), it can be used again in the helmet cooling system. The rate of cooling of PCM is compared between the ice box cooling and room temperature cooling methods in Figure 15.

CHAPTER 5. CONCLUSION

This work investigated the utilization of phase change materials in football helmets to maintain a comfortable head temperature for the athletes. A copper pouch, with aluminum honeycomb filled with PCM material has been used for the helmet cooling element. The impact of solar radiation and wind speed on the cooling system was examined. PCM pouch thicknesses have been analyzed for the optimization of heat flux values using Ansys Mechanical APDL software. The effect of pouch thickness on the cooling system was examined. In addition, the recharge time of the PCM to reuse them in helmets for cooling has also been analyzed. The results indicate that the cooling system is able to maintain a comfortable head temperature for up to 56 minutes. An optimum pouch thickness of 17 mm provides best cooling. Therefore, by using PCM, the temperature inside the helmet can be maintained at an average body temperature of 36°C for a prolonged period of time. The heat accumulated in the PCM pouch can be released by placing it in an ice box cooler for 10 minutes or placing it at room temperature for one hour to solidify it before reusing. The estimated cost of a cooling pouch is $25. Although the emphasis of this study is on the cooling of a football helmet, the results may be applied to the implementation of phase change material cooling solutions.

REFERENCES

[1] Armstrong, L. E., Casa, D. J., Millard-Stafford, M., Moran, D. S., Pyne, S. W., & Roberts, W. O. (2007). Exertional heat illness during training and competition. *Medicine & Science in Sports & Exercise*, *39*(3), 556-572.

[2] Brothers, R. M. (2004). *Wearing a Football Helmet Exacerbates Thermal Load During Exercise in Thermoneutral and Hyperthermic Exercise* (Doctoral dissertation).

[3] Rasch, W. E. N. C. H. E., & Cabanac, M. I. C. H. E. L. (1993). Selective brain cooling is affected by wearing headgear during exercise. *Journal of Applied Physiology*, *74*(3), 1229-1233.

[4] Schultz, J., Kenney, W. L., & Linden, A. D. (2014). Heat-related deaths in American football: An interdisciplinary approach. *Sport History Review*, *45*(2), 123-144.

[5] Mueller, F. O., & Colgate, B. (2013). Annual Survey of Football Injury Research, 1931-2012. *Retrieved from Website http://. unc. edu/depts/ncsi/2012FBInj. Pdf*.

[6] McCullough, E. A., & Kenney, W. L. (2003). Thermal insulation and evaporative resistance of football uniforms. *Medicine and science in sports and exercise*, *35*(5), 832-837.

[7] Armstrong, L. E., Johnson, E. C., Casa, D. J., Ganio, M. S., McDermott, B. P., Yamamoto, L. M., ... & Emmanuel, H. (2010). The American football uniform: uncompensable heat stress and hyperthermic exhaustion. *Journal of athletic training*, *45*(2), 117-127.

[8] Rasch, W., Samson, P., Cote, J., & Cabanac, M. (1991). Heat loss from the human head during exercise. *Journal of applied physiology*, *71*(2), 590-595.

[9] Nunnely, S. A. (1971). Head cooling in work and heat stress. *Aerospace Med.*, *42*, 64-68.

[10] Buist, R. J., & Streitwieser, G. D. (1988, March). The thermoelectrically cooled helmet. In *Proceeding* (pp. 88-94).

[11] Cao, L., Han, J., Duan, L., & Huo, C. (2017). Design and Experiment Study of a New Thermoelectric Cooling Helmet. *Procedia Engineering*, *205*, 1426-1432.

[12] Waters, W. A. (1970). *U.S. Patent No. 3,548,415*. Washington, DC: U.S. Patent and Trademark Office.

[13] Pierce, B. E. (2007). *U.S. Patent No. 7,207,071*. Washington, DC: U.S. Patent and Trademark Office.

[14] Jwo, C. S., & Chien, C. C. (2007). *U.S. Patent Application No. 11/312,753*.

[15] Tan, F. L., & Fok, S. C. (2006). Cooling of helmet with phase change material. *Applied Thermal Engineering*, *26*(17-18), 2067-2072.

[16] Fok, S. C., Tan, F. L., & Sua, C. C. (2011). Experimental investigations on the cooling of a motorcycle helmet with phase change material (PCM). *Thermal Science*, *15*(3), 807-816.

[17] Ghani, S., ElBialy, E. M. A. A., Bakochristou, F., Gamaledin, S. M. A., & Rashwan, M. M. (2017). The effect of forced convection and PCM on helmets' thermal performance in hot and arid environments. *Applied Thermal Engineering*, *111*, 624-637.

[18] Sinnappoo, K., Nayak, R., Thompson, L., & Padhye, R. (2020). Application of sustainable phase change materials in motorcycle helmet for heat-stress reduction. *The Journal of The Textile Institute*, 1-9.

[19] Hu, W., Liu, Z., Yuan, M., Peng, Y., Meng, X., & Hou, C. (2020). Composite design and thermal comfort evaluation of safety helmet with PCM cooling. *Thermal Science*, (00), 250-250.

[20] Cabeza, L. F., Mehling, H., Hiebler, S., & Ziegler, F. (2002). Heat transfer enhancement in water when used as PCM in thermal energy storage. *Applied thermal engineering*, *22*(10), 1141-1151.

[21] Zalba, B., Marin, J. M., Sanchez-Valverde, B., & Cabeza, L. F. (2002). Free cooling; an application of PCMS in TES. *IEA, ECES IA, Annex*, *17*(3).

[22] Raoux, S. (2009). Phase change materials. *Annual Review of Materials Research*, *39*, 25-48.

[23] Fok, S. C., Shen, W., & Tan, F. L. (2010). Cooling of portable hand-held electronic devices using phase change materials in finned heat sinks. *International Journal of Thermal Sciences*, *49*(1), 109-117.

[24] Tarlochan, F., Hamouda, A. M. S., Mahdi, E., & Sahari, B. B. (2007). Composite sandwich structures for crashworthiness applications. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, *221*(2), 121-130.

[25] Padmanabhan, P. V., & Murthy, M. K. (1986). Outward phase change in a cylindrical annulus with axial fins on the inner tube. *International Journal of Heat and Mass Transfer*, *29*(12), 1855-1868.

[26] Mishra, A., Shukla, A., & Sharma, A. (2015). Latent heat storage through phase change materials. *Resonance*, *20*(6), 532-541.

[27] Jovanović, D. B., Karkalić, R. M., Tomić, L. D., Veličković, Z. S., & Radaković, S. S. (2014). Efficacy of a novel phase change material for microclimate body cooling. *Thermal Science*, *18*(2), 657-665.

[28] Katekar, V., & Khatri, V. (2012). Helmet cooling with phase change material. *Department of Mechanical engineering, SB Jain Institute of Technology, Nagpur*.

[29] Mahmoud, S., Tang, A., Toh, C., Raya, A. D., & Soo, S. L. (2013). Experimental investigation of inserts configurations and PCM type on the thermal performance of PCM based heat sinks. *Applied Energy*, *112*, 1349-1356.

[30] Wirtz, R. A., Zheng, N., & Chandra, D. (1999, March). Thermal management using" dry" phase change material. In *Fifteenth Annual IEEE Semiconductor Thermal Measurement and Management Symposium (Cat. No. 99CH36306)* (pp. 74-82). IEEE.

[31] Clark, R. P., & Toy, N. (1975). Forced convection around the human head. *The Journal of physiology*, *244*(2), 295-302.

[32] Froese, G., & Burton, A. C. (1957). Heat losses from the human head. *Journal of Applied Physiology*, *10*(2), 235-241.

[33] Huizen, J. (2017, December 5). *What should you know about hyperthermia?* Medical News Today. https://www.medicalnewstoday.com/articles/320226

[34] Wikipedia contributors. (2021, January 27). *Hyperthermia*. Wikipedia. https://en.wikipedia.org/wiki/Hyperthermia

[35] *Body Temperature | Michigan Medicine*. (2020, February 26). Michigan Medicine. https://www.uofmhealth.org/health-library/hw198785#hw198839

[36] *What Is the Normal Body Temperature Range?* (2020, October 6). Healthline. https://www.healthline.com/health/what-is-normal-body-temperature

[37] Casa, D. J., Armstrong, L. E., Ganio, M. S., & Yeargin, S. W. (2005). Exertional heat stroke in competitive athletes. *Current sports medicine reports*, *4*(6), 309-317.

[38] Navarro, C. S., Casa, D. J., Belval, L. N., & Nye, N. S. (2017). Exertional heat stroke. *Current sports medicine reports*, *16*(5), 304-305.

[39] Goldsborough, R. (2007). *U.S. Patent No. 7,296,304*. Washington, DC: U.S. Patent and Trademark Office.

[40] Farid, M. M., Khudhair, A. M., Razack, S. A. K., & Al-Hallaj, S. (2004). A review on phase change energy storage: materials and applications. *Energy conversion and management*, *45*(9-10), 1597-1615.

[41] Sinnappoo, K., Nayak, R., Thompson, L., & Padhye, R. (2020). Application of sustainable phase change materials in motorcycle helmet for heat-stress reduction. *The Journal of the Textile Institute*, *111*(11), 1547-1555.

[42] *Expanded Polystyrene (EPS)*. (2017). DOME. https://www.helmetfacts.com/materials/expanded-polystyrene-eps/#:%7E:text=Expanded%20Polystyrene%20(EPS)%20%3C%20back,management%20applications%20like%20automobile%20bumpers

[43] Satterthwaite, K. (2017). Plastics Based on Styrene. In *Brydson's Plastics Materials* (pp. 311-328). Butterworth-Heinemann.

[44] Osswald, T. A., Baur, E., Schmachtenberg, E., Oberbach, K., & Brinkmann, S. International Plastics Handbook: The resource for plastics engineers. 2006. *Munich: Hanser*.

[45] *Heat Exhaustion or Heat Stroke? A Guide*. (2018, July 20). Inside Climate News. https://insideclimatenews.org/infographics/heat-exhaustion-or-heat-stroke-guide/

[46] *Heat Stress Related Illness | NIOSH | CDC*. (2018, June 6). Centers for Disease Control and Prevention (CDC). https://www.cdc.gov/niosh/topics/heatstress/heatrelillness.html

[47] Manchester, S. M. (2018, January 4). *The N.F.L.'s Fastest Players? You Might Be Surprised*. The New York Times. https://www.nytimes.com/2018/01/04/sports/football/nfl-speed-leonard-fournette.html

[48] *HEAT FLUX*. (2011, February 2). Thermopedia. https://thermopedia.com/content/833/

[49] *Phase-Change Materials*. (2016, February 11). NASA. https://www.nasa.gov/offices/oct/40-years-of-nasa-spinoff/phase-change-materials/