Helmet Cooling With Phase Change Material

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ABSTRACT
Human life is so precious and valuable, that it should not be compromised under any cost. In a latest survey, conducted it is mentioned that nearly 62% of mortality in road accidents occur due to head injury, where the rider has not worn the helmet. It is not that people are very negligent about their lives on road, but that they experience dozens of discomfort by wearing helmets. But the most common discomfort is that, heavy sweat occurs due to excessive heat formation. This mainly focuses on absorbing the heat produced inside the helmet. To achieve this, a suitable phase change material (PCM) is packed into a pouch and placed between the helmet and the wearer head. The heat from the wearer head is transferred to the PCM by conduction through a heat collector which is spread over the wearer head. No electrical power supply is needed for the cooling system. The temperature on the wearer head is maintained just above the PCM temperature, thus the wearer would not suffer from dangerous hot environment on the head which will affect the wearer alertness. The cooling unit is able to provide comfort cooling up to 2.10 h when the PCM is completely melted. The stored heat from the PCM pouch would then have to be discharged by immersing in tap water for about 13 min to solidify the PCM before re-use. The PCM helmet cooling system is simple and has potential to be implemented as a practical solution to provide comfort cooling to the motorcycle riders.

Keywords
Phase Change Material, Latent heat storage, Motorcycle Helmet, Helmet Cooling.

1. INTRODUCTION
This project deals with the design of a helmet cooling system using phase change material (PCM) to absorb and to store the heat produced by wearer head so as to achieve comfort cooling for the wearer.

The PCM is packed into a pouch and placed between the helmet and the wearer head. The heat from the wearer head is transferred to the PCM by conduction through a heat collector which is spread over the wearer head. No electrical power supply is needed for cooling system. The temperature on the wearer head is maintained just above the PCM temperature, thus the wearer would not suffer from an uncomfortable and dangerous hot environment on the head which will affect the wearer alertness. The helmet has two principal protective components: a thin, outer shell made of acrylonitrile butadiene strene (ABS) plastic, fiberglass or Kevlar and a soft, thick, inner liner about one-inch thickness usually made of expanded polystyrene foam or expanded polypropylene foam. The foam liner is very similar to that used in refrigerators as thermal insulation. The hard outer shell prevents puncture of helmet by sharp pointed object and provides the framework to hold the inner liner. The inner foam liner is to absorb the crush during an impact. The one-inch thickness of insulation lining the interior of helmet restricts and virtually eliminates the heat exchange with the outside wall of the most effective part of the body. This creates an uncomfortable and dangerous hot environment to the head of the wearer. The interior of the helmet can quickly rise to the temperature between 37^0C and 38^0C. When this occurs, the physiological and psychological effects on the rider are very real and potentially dangerous due to a deadening of the senses and a decrease in ability to concentrate. It is observed that head cooling is the most efficient of any other part of the body because it has the highest skin temperature as well as large constant-volume blood flow [2]. Head cooling has been perceived as an essential necessity to provide overall thermal comfort to the rider. A helmet cooling system uses phase change material (PCM) to absorb all the heat generated from the head at a relatively constant temperature to provide cooling of the head and thus, the interior is maintained at a certain cooled temperature of the PCM and creates electrical power supply. The PCM is enclosed in a pouch and placed between the head and the helmet. When the head skin temperature is above the melting temperature of the PCM, the PCM begins to melt as it absorbs the heat from the head. A PCM-cooled system can be implemented in any kind of safety helmet. The PCM-cooled system is ideal for any kind of safety helmet due to its simple structure and operation without requiring a power supply. The design and structure of safety helmets may differ according to their intended usage. For example, a safety helmet used by motorcyclist and race car drivers and a safety helmet used by construction site workers will be quite different in their structures. Despite their different structures, these helmets require a good cooling system. The PCM-cooled helmet will be suitable for these safety helmets. In this paper, the design implementation of a helmet cooling system using PCM is investigated. The PCM-cooled system is designed for the motorcycle helmets having short riding period up to about 2.10 h. After that, the stored heat from the PCM would have to be discharged to the ambient air for about 13–25 min before the helmet can be used again. Some practical solutions can be implemented to cool the head. The popular and marketable techniques are the air cooled system using air blower or vents [3]. Some cooling systems use liquid to cool the air blowing into the helmet. In some air cooled system, the air duct is installed to the chin bar of the helmet. Such design is intended for only the race car drivers. The air cooling systems use vents to allow the natural air flow to pass through the interior of the helmet to remove heat. Although these designs may be used for motorcycle riders, it is debatable whether these systems are suitable for tropical countries that have high ambient temperatures. Thus, an alternative simpler cooling system to be implemented for the motorcycle helmet is desirable. More recently, Buist and Streitwieser [7] use thermoelectric cooler (TEC) as a heat pump to dissipate the heat from the interior of the helmet to a finned heat sink located outside the helmet. The thermoelectric cooling system is shown to be a viable method to cool the head. However, it requires connection to direct current (DC) power supply to operate the thermoelectric cooler. The DC power supply can come from the battery of the motorcycle or a small battery can be implemented inside the helmet. The thermoelectric cooling design is simple. The design with the battery inside the helmet makes the helmet heavier. And it is also dangerous to have a design with a dangling electrical wire connection from the helmet to the motorcycle battery. This paper proposed an alternative simple solution to the cooling of the motorcycle helmet.

A helmet cooling system eliminating the requirement of the power uses phase change material (PCM) to absorb all the heat.

2. DESIGN OF PCM-COOLED HELMET

The figure 1 below illustrates the schematic diagram of PCM-cooled helmet. The key component of the helmet cooling system is the PCM pouch in which PCM is enclosed. The PCM is enclosed by thin flexible aluminum foil to form a pouch. Flexible heat collector made of copper provides thermal path for conducting heat transfer from the wearer head to the PCM pouch. The heat collector is attached to a vinyl cushion which is filled with a water based solution. The vinyl cushion provides a comfortable interior for the helmet. The problem of overcooling on the head does not occur as the head skin temperature is maintained at a temperature which is near to the melting temperature of PCM. The head skin temperature will never go below the melting temperature of the PCM. The most important aspect is the choice of PCM material. When the head temperature turns to be above 30^0c, the PCM begins to melt to provide a cooling effect on the head. When the skin temperature goes below 30^0C, the PCM pouch provides a warming effect. Various PCM, such as organic based paraffin [6] other as inorganic PCM like salt hydrates and yet another as certain metallic alloys, and dry [9] PCM can be used. Each has its own strength and weakness for the application. The paraffin PCM is relatively inexpensive and widely available. Paraffin has higher heat storage capacity per unit volume. However, the liquid phase of the PCM gives rise to problems of containing the fluid which may result in increased complexity and cost. Salt hydrates are generally corrosive as they absorb and loose water during phase change, and tend to form partially hydrated crystals. Some metallic alloys have been used in high performance military systems and have higher latent heat per unit volume compared to paraffin PCM. However, the density of metallic alloy is higher resulting in relatively heavier system.

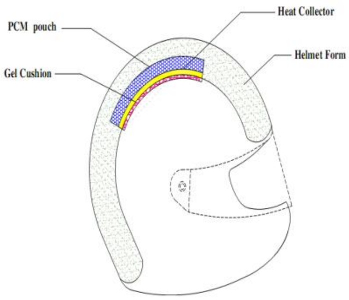

Fig. 1: - Schematic diagram for PCM-cooled helmet

Dry PCM include micro-encapsulated solid–liquid phase change composites and solid–solid organic phase change compounds. They can eliminate liquid containment problems and have higher thermal conductivity. The discharging time (solidification) is shorter compared to the paraffin. However, the dry PCM is expensive and the heat storage capacity per unit volume is much lower than the paraffin wax.

Fig. 2: -Insulator casing

One of the design problems with the PCM-cooled helmet is the time limitation on the usage of the helmet. When the PCM is completely melted, it can no longer maintain its temperature to store the excess heat. The temperature of the liquid PCM will rise as heat is continually transferred from the head to the PCM. For a given amount of PCM in the pouch, the length of time that the PCM can be used to absorb the heat depends on the amount of heat produced by the wearer and the ambient temperature. The period of cooling can be lengthened by using a large amount of PCM. However, there is space limitation to the amount of PCM that can be stored in the helmet.

The concept of surface area can be used to shorten the discharge time. PCM usually has a very low heat conductivity of the material which would lead to low heat transfer rate. One way to enhance the heat transfer is to use fins [10], honey-combed structure, metal matrices (wire mesh), or addition of high conductivity particles or graphite inside the PCM pouch. Addition of additives will increase the internal heat transfer rate, but they will also contribute to the increased weight and volume of cooling system.

Furthermore, the PCM pouch has to be designed for ease of removal of the pouch from the helmet for re-use. Another design problem concerns the safety feature requirement of the helmet with the incorporation of the PCM-cooled system into the helmet.

3. DESIGN SPECIFICATIONS

The PCM-cooled helmet is designed to maintain the head skin temperature at about $T_{skin} = 30^0C$. It is designed to be capable of cooling the head continuously up to 2.10 h which is referred to as the loading time, dt_{load} = 2.10 h. After the loading time, the stored heat in the PCM pouch needs to be dissipated to the ambient which is referred to as the discharging time, $dt_{discharge}$. The helmet is designed to allow quick and easy retrieval of the PCM pouch from the helmet for discharging. The PCM pouch can be left on a table for heat dissipation to the ambient by natural convection, or the pouch can be immersed in water at room temperature to enhance heat dissipation to shorten the discharging time. If the PCM pouch stays inside the helmet, the discharging time will be longer.

Fig. 3: - Heat sink

4. CALCULATIONS

Figure 4 shows the cross-section of the helmet with the PCM-cooled system [8]. The sources of heat to the PCM in the pouch come from the wearer head and the hot ambient air around the helmet. The heat generated by the wearer head is about 116 W/m^2 [3], producing about Q_{head} =15W for an average size head. The amount of PCM, m_{PCM}, required is determined from one-dimensional heat transfer calculations using thermal resistance network shown in Figure: - 1 [8]. Heat flows from the head through the thermal resistances of the cushion and heat collector to the PCM in the pouch. The helmet is heated up by the hot ambient air and also through the skin friction heating by the air flowing across the surface of helmet. Thus, a certain amount of heat, Q_{in}, flows from the ambient through the surface of helmet through the shell thickness and foam and finally reaches into the PCM in the pouch. The surface temperature of the helmet is estimated to be at $T_{surface} = 60^0C$. The PCM melting temperature, T_{PCM}, is taken as 30^0C.

The calculations to determine the amount of PCM required meeting the design specifications are shown below. The thermal resistances of the foam (R_{foam}), helmet shell (R_{shell}), heat collector ($R_{collector}$) and gel cushion ($R_{cushion}$) are determined based on one-dimensional heat conduction through a plane wall. The symbols t_{foam}, A_{foam}, and k_{foam} are the thickness, surface area, and thermal conductivity of the foam, respectively

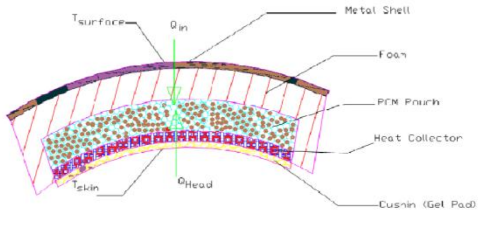

Fig.4: - Cross-section of the helmet showing the PCM pouch, heat collector and cushion.

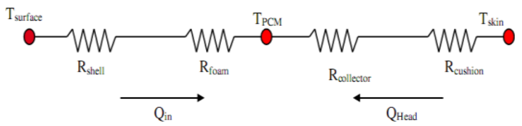

Fig.5: Heat flow through the thermal resistances

$$R_{\text{foam}} = \frac{t_{\text{foam}}}{A_{\text{foam}} k_{\text{foam}}} = \frac{1.7 \times 10^{-2}}{0.045 \times 0.01} = 37.8 \text{ K/W}$$

$$R_{\text{shell}} = \frac{t_{\text{shell}}}{A_{\text{shell}} k_{\text{shell}}} = \frac{0.3 \times 10^{-2}}{0.045 \times 50} = 1.33 \times 10^{-3} \text{ K/W}$$

$$R_{\text{collector}} = \frac{t_{\text{collector}}}{A_{\text{collector}} k_{\text{collector}}} = \frac{0.5 \times 10^{-2}}{0.03 \times 385} = 4.33 \times 10^{-4} \text{ K/W}$$

$$R_{\text{cushion}} = \frac{t_{\text{cushion}}}{A_{\text{cushion}} k_{\text{cushion}}} = \frac{0.5 \times 10^{-2}}{0.03 \times 1.6} = 0.1 \text{ K/W}$$

$$Q_{\text{in}} = \frac{T_{\text{surface}} - T_{\text{PCM}}}{R_{\text{shell}} + R_{\text{foam}}} = \frac{60 - 28}{1.33 \times 10^{-3} + 37.8} = 0.8 \text{ W}$$

$$Q_{\text{Head}} = \frac{T_{\text{skin}} - T_{\text{PCM}}}{R_{\text{collector}} + R_{\text{cushion}}} = \frac{T_{\text{skin}} - 28}{4.33 \times 10^{-4} + 0.1} = 15 \text{ W}$$

$$\Rightarrow T_{\text{skin}} = 29.5\,^{\circ}\text{C}$$

Assuming that, maximum amount of heat from ambient air and head is absorbed by the PCM over a loading time of 2.10 h, on the basis of experiment conducted after fabrication the amount of PCM required is determined to be about 910 gm and the volume occupied by the PCM is found out to be $621 cm^3$.

$$(Q_{\text{in}} + Q_{\text{head}}) \times \Delta t_{\text{load}} = m_{\text{PCM}} \lambda_{\text{PCM}} \Rightarrow m_{\text{PCM}} = 0.903 \text{ kg}$$

$$m_{\text{PCM}} = V_{\text{PCM}} \rho_{\text{PCM}}$$

$$V_{PCM} = 0.910/1464$$

$$V_{PCM} = 621 \text{ cm}^3$$

The analysis shown was performed for steady-state under idealized conditions. In the actual design of the helmet, a factor of safety of about 5% - 10% should be included to cater for non-ideal conditions in the practical environment.

5. PCM SELECTION

Since the head skin temperature of the wearer is designed to maintain at around 30^0C, the PCM, sodium sulfate decahydrate, which has the melting temperature of 30^0C is chosen. The sodium sulfate decahydrate PCM belongs to the salt hydrate type. It has relatively high storage capacity per unit volume [11] and it is not flammable. It is also relatively inexpensive and widely available in the market. The sealed pouch stores the PCM in both solid and liquid state and is designed to shorten the discharging time (re-solidification from liquid to solid state). The properties of the sodium sulfate decahydrate PCM are shown in Table I.

Table 1 Properties of PCM Sodium sulfate decahydrate

Description	**Value**
Working range	$19 – 39^0c$
Melting temperature	30^0c
Maximum temperature	60^0c
Specific heat	$1 W h/kg/^0c$
Density	$1464 kg/m^3$
Latent heat	35 W h/kg
Thermal conductivity	$0.5 – 0.7 W/m/^0c$

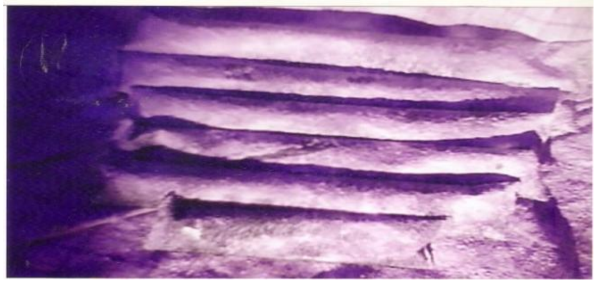

Fig.6: -PCM pouch

One of the main problems with using pure salt hydrates is the super cooling. The liquid PCM can be cooled several degree Celsius below the melting temperature of PCM before solidification starts, thus giving a wide melting and solidification temperature range. The phase change does not occur at a uniform melting temperature. To overcome the super cooling problem, a nucleating agent such as Borax can be added to the salt [12] to narrow the range of phase change.

From the thermal analysis shown in earlier section, an estimated amount of 910 g of PCM is required to absorb and to store the heat dissipated from the head and the ambient air, so as to maintain the head skin temperature, up to 2.10 h. The required volume of the PCM is about $621 cm^3$. Additional extra volume of .5% should be provided in the design to account for the volume expansion of the PCM.

6. PCM POUCH DESIGN

Thin and flexible aluminum foil is used as material for the pouch. Aluminum has high thermal conductivity and the thin foil makes effective heat transfer between heat collector and paraffin. Based on the required mass of the PCM, the dimension of the pouch shown in Figure below [8] is estimated to be 22 x 15 x 1.35cm. The pouch has large heat transfer surface area to shorten the discharging time. The thickness of the pouch is thin so that the installation of the PCM pouch into the helmet will not affect the primary safety requirement of the helmet. When the PCM melts, liquid PCM will expand in volume by about 0.1%. Thus, the pouch has to be made larger to allow volume expansion of the PCM when it melts.

The pouch is subdivided into several compartments with each compartment holding certain amount of PCM instead of one whole bag. This is to reduce the movement of the liquid inside the pouch as the PCM melts.

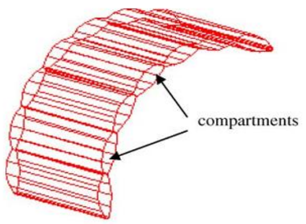

Fig. 7: - Pouch containing PCM

The pouch is subdivided into several compartments with each compartment holding certain amount of PCM instead of one whole bag. This is to reduce the movement of the liquid inside the pouch as the PCM melts. The installation of the PCM pouch, heat collector and gel cushion is shown in [8] Figure below: -

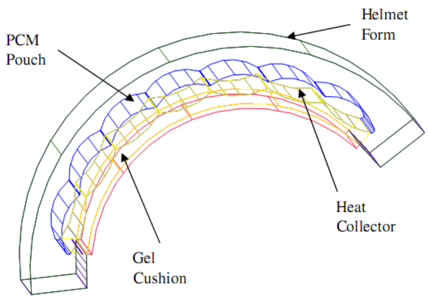

Fig. 8: -Assembled PCM-cooled helmet

The PCM pouch is designed to absorb and store the heat generated from the wearer head up to 2.10 h. After about 2.10 h, the PCM becomes completely liquid. The PCM pouch then needs to be unloaded to bring it back to the solid state before it can be re-used. For discharging, the pouch can be left in the ice water at 0^0C or normal water from the tap at room temperature (about 20^0C). The below empirical heat transfer correlations for natural convection heat transfer [13] from a hot surface facing up or down are used to determine average heat transfer coefficient for the upper and lower surfaces of PCM pouch.

$$\text{Hot surface facing up: } \overline{Nu}_L = 0.15 Ra_L^{1/3} \quad (10^7 < Ra_L < 10^{11})$$

$$\text{Hot surface facing down: } \overline{Nu}_L = 0.27 Ra_L^{1/4} \quad (10^5 < Ra_L < 10^{10}$$

Assuming all the stored heat in the PCM is discharged to the water by natural convection, the discharging time of the PCM pouch for complete solidification is estimated to be about 7 min in ice water and 15 min in tap water.

$$\bar{h}_L A_{\text{pouch}} (T_{\text{PCM}} - T_{\text{water}}) \times \Delta t_{\text{discharge}} = (Q_{\text{in}} + Q_{\text{head}}) \Delta t_{\text{load}}$$

$$\Rightarrow \Delta t_{\text{discharge}}$$

7. HEAT COLLECTOR AND CUSHION DESIGN

Heat collector is made of light copper plate material with flexible braided copper wire. It collects the heat generated from the head and conducts it to the PCM pouch. It has to be flexible for installation along the curvature of the helmet. The dimension of the heat collector shown in Figure [8] below is 22 x 15 x 0.5 cm.

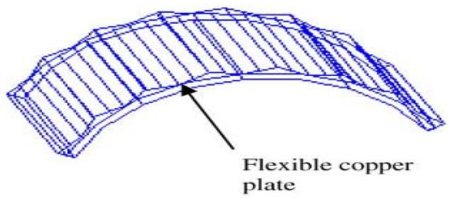

Fig.9: - Heat collector

The curvature of the heat collector is designed to fit in nicely to the PCM pouch to provide good thermal contact. It is placed between the pouch and vinyl cushion which is filled with a water-based solution (gel). The vinyl cushion provides a comfortable interior for the head to fit in. The liquid gel not only provides the comfort but also serves as the heat transfer medium between the head and the heat collector. The dimension of the gel cushion is 22 x 15 x 0.3 cm.

The complete assembly of PCM-cooled helmet comprises of PCM pouch, heat collector and gel cushion as shown below in figure, these material are such that they don't affect the design of the helmet.

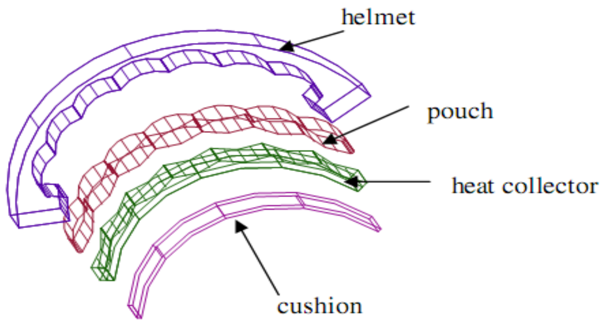

Fig.10: - Classified view of the PCM-cooled system

The designing of system is such that whole PCM-cooled system can be easily ejected after getting discharged. The PCM pouch can be detached separately from the assembly so as to allow the discharging of stored heat by immersing the pouch into water at room temperature or ice water.

8. CONCLUSION

From the above conducted experiment and calculated heat resistance using one-dimensional heat conduction equation it is clear that this PCM-cooled system can be implemented in conventional helmet to provide comfort, thus the wearer would not suffer from an uncomfortable and dangerous hot environment on the head which will affect the wearer alertness. The PCM-cooled system conveniently cools helmet for 2.10 h with the only limitation that once it gets discharged it is to be recharged for re-use.

9. REFERENCES

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