EXPERIMENTAL INVESTIGATIONS ON THE COOLING OF A MOTORCYCLE HELMET WITH PHASE CHANGE MATERIAL

by

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The thermal comfort of motorcycle helmet during hot weather is important as it can affect the physiological and psychological condition of the rider. This paper examines the use of phase change material to cool a motorcycle helmet and presents the experimental investigations on the influence of the simulated solar radiation, wind speed, and heat generation rate on the cooling system. The results show that with the phase change material cooled helmet is able to prolong the thermal comfort period compared to a normal helmet. The findings also indicate that the heat generation from the head is the predominant factor that will affect the phase change material melting time. Simulated solar radiation and ram--air due to vehicle motion under adiabatic condition can have very little influence on the phase change material melting time. The results suggested that the helmet usage time would be influenced by the amount of heat generated from the head. Some major design considerations based on these findings have been included. Although this investigation focuses on the cooling of a motorcyclist helmet, the findings would also be useful for the development of phase change material cooling systems in other applications.

Key words: *phase change material, cooling helmet, thermal comfort*

Introduction

The helmet is a critical piece of safety equipment for a motorcyclist. Although there are many varieties of helmet designs available in the market, the product must essentially protect the head against injuries, maintain user comfort, and appeal to the user in terms of cost and aesthetics. It is imperative that the motorcyclist is comfortable with wearing the helmet. Uncomfortable personal protective equipment can affect performance and create hazards that could lead to accidents [1]. There are numerous factors that can influence the user comfort level. One of these factors is dependent on temperature. The comfortable thermal condition for the head is around 34.5 °C [2]. During the hot climate season, the temperature inside the helmet could reach 50 °C under sunny weather if there is no wind [3] and hypothermia can be induced [4]. To avoid this problem, it is desirable to maintain the helmet interior temperature to around the body temperature of 38 °C [5].

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The temperature inside the helmet could be affected by both the heat gained from solar radiation and the heat generated from the head. In a hot day with no wind, the helmet surface temperatures can reach 50 to 60 °C [6]. As a result, heat could be transferred by conduction from the outer surface to the interior due to the temperature gradient across the helmet layer. The main means to minimize the heat gained from solar radiation include the use of appropriate color paint and reflective surface materials. Hsu *et al.* [3] found that the temperature of white helmet can be 4 to 7 °C lower than other colored helmets and the proper use of reflective materials on the surface can also result in lower interior temperature. Insulation in the form of inner lining is also a popular solution. However, insulation can also hinder the dissipation of the heat generated from the head to the ambient in cold weather conditions. It is estimated that about 40 to 50% of the total heat produced within the body is released through the head [7]. Clark and Toy [8] found that the heat loss from the head is about 10 W for a skin temperature of 33 °C and ambient temperature of 23 °C. To dissipate the heat generated from the head, most helmets rely on forced convection generated by the relative motion between the motorcyclist and the air during the ride. The forced convection is created on the outer surface of helmet as well as on the head surface. Holland *et al.* [9] found that the exchange of air between the helmet microclimate and the ambient environment was fastest for helmets with top vents. However for safety reason, it is desirable for the motorcycle helmet to fully cover the top of the head. Hence, creating adequate ventilation at the top of the motorcycle helmet may not be feasible. The lack of ventilation at the top of the motorcycle helmet can greatly hinder the forced convection process.

The helmet thermal discomfort issue has been relatively ignored for many years. Recently there are renewed interests in this area and active cooling systems had been investigated. An example is the application of thermoelectric (TE) cooling module [5] to dissipate the heat from the inner layer of helmet to an outboard heat sink. Another example is the airflow cooled helmet [10], which uses a blower to draw cold air from the ambient into the helmet to provide the cooling. Solar power-operated cooling system [11] had also been investigated – the electricity generated from a solar cell was used to power a TE cooling module and a small fan so that cold air can be delivered into the helmet.

Generally, there are pros and cons associated with these cooling solutions. For example, some designs need external power sources to activate the cooling system. Extra efforts may be needed to install and maintain these cooling solutions. Other designs could involve major modifications, which may affect the helmet structural strength. Furthermore, the extra costs associated with the implementation of these solutions have to be considered. A good solution should be cheap, compact, effective, and easy to implement. One simple alternative passive means is to use phase change material (PCM), which has a high latent heat of melting [12]. Heat inside the helmet can be effectively stored in the PCM as it changes phase from solid to liquid. Since the phase change occurs at uniform melting temperature, the helmet interior temperature can be maintained until the PCM is fully melted. The cooling system can be produced with a simple design, such as encapsulating the solid PCM within a thin metal casing. Molten PCM can be re-solidified by dissipating heat to the surroundings when the helmet is not in use. Tan *et al.* [13] had proposed the conceptual design of a PCM--cooled helmet. Theoretically, the effective use of PCM has great potential for cooling a helmet. However, to further develop the concept, it is necessary to identify the factors that would influence the PCM cooling in this application.

This paper extends on the work of Tan *et al.* [13]. It aims to identify experimentally the influences of the simulated solar radiation, wind speed, and heat generation rate on the

PCM cooling process. These influences would assist the detailed design of a PCM-cooled helmet.

Experimental design, set-up and testing

The study involved testing a helmet installed with a simple phase change material storage unit (PCMSU) in a wind tunnel. In this work, a half face standard size motorcycle helmet was studied. A black helmet was used as it can absorb more heat compared to a white one. Figure 1 shows the schematic diagram of the helmet with the PCMSU embedded inside it. The thermal properties of the helmet materials are given in tab. 1. The PCMSU casing is made of thin aluminum plates. The PCM used is n-octadecane. This material was selected due to its high latent heat value, non-toxic characteristic and affordable price. General properties of n-octadecane are given in tab. 2. The PCMSU, which has a storage capacity of 54.5 cm^3, was filled with only 49 cm^3 of solid n-octadecane to allow for the PCM expansion during the melting process [14]. This small amount was used to study the cooling performance at the top of the head. A heater (silicon rubber heater from MINCO Inc.) was used to simulate the heat generated from the top of the head. This heater was attached to the bottom of the PCMSU. The heat generated from the heater was regulated by an AC power supply. Four internal fins were installed in the PCMSU to increase the heat transfer surface area between the heat source and the PCM. Screws were used to secure the casing to a cover plate. Rubber gasket was used to prevent the leakage of PCM from the casing. In addition, all gaps were sealed with epoxy glue and silicon glue. For comparison purposes, an empty PCMSU (*i. e*. without PCM) was fitted into another similar helmet. The difference in weights between two helmets is less than 0.05 kg.

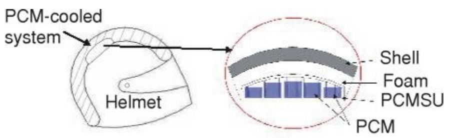

Figure 1. Schematic diagram of PCM--cooled helmet

Table 1. Thermal properties of helmet materials

Description	Value
Outer shell	Thermal conductivity 50 W/mK
Outer shell	Emissivity 0.75
Foam	0.01 W/mK

Figure 2 shows the schematics of the experimental set-up in the wind tunnel. The helmet is secured firmly to the platform using bolts and nuts to prevent any movement or vibration. A heat radiator (*i. e*. JBL Ceramic 150 W heat radiator with wavelength of about 3 to 15 μm) is used to simulate the solar radiation. This radiator is mounted downstream on the roof of the wind tunnel at an angle of 45°. The horizontal distance between the radiator and helmet is adjusted such that the heat is

Table 2. Properties of n-octadecane

Description	Value
Melting point	28-30 °C
Boiling point	316-317 °C
Specific heat capacity	2330 J/kgK
Latent heat	243500 J/kg
Density	782.2 kg/m^3
Thermal conductivity	0.34 W/mK

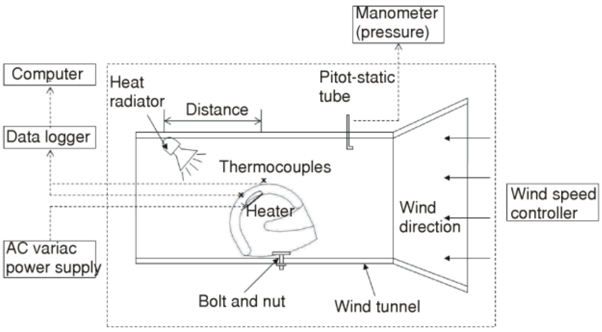

Figure 2. Schematic of the experimental set-up

able to raise the temperature on the outer surface of helmet from 30 °C ambient temperature to 50 to 60 °C in 30 minutes under no wind condition. The heat flux that reaches the surface of the helmet would be about 198 W/cm^2 [6]. This heat flux was measured with a calibrated radiometer (*i. e.* H111C). The test condition, which simulated a rider wearing a helmet in a 30 °C sunny day in Singapore, is validated by examining the temperature distribution over time using thermocouples placed at different positions on the helmet surface. The wind which simulates the ram-air due to vehicle motion is generated by the wind tunnel. A Pitot-static tube is used to measure the stagnation and static pressures of the moving air. The wind speed in the tunnel can be adjusted by a controller based on the pressure difference between stagnation and static pressures.

Eleven strategically placed K-type thermocouples were used to determine the average temperature on the helmet surface, heater temperature, average PCMSU temperature and the average PCM temperature. Three thermocouples are located on the surface of the PCMSU casing and another three are inserted into the PCMSU to measure the PCM temperatures. One thermocouple is placed at the bottom of the heater. Four thermocouples are positioned on the surface of helmet. All the thermocouples were calibrated to within an accuracy of 0.5 °C and connected to a data logger. The captured temperatures were output to a computer.

The experimental parameters to be investigated are given in tab. 3. Experiments were first conducted to determine the effectiveness of the PCM cooling solution. These were accomplished using the normal helmet (*i. e.* with the empty PCMSU) followed by the PCM-cooled helmet. The heater power, wind speed and simulated solar radiation were held constant in these experiments. Next a series of experiments were conducted on the PCM-cooled helmet to investigate the effects of simulated solar radiation, heater power, and wind speed based on two different heat transfer conditions. The effect of simulated solar radiation on the PCM was investigated by switching the radiator on and off. Comparison of the effects for different heat powers on the PCM melting time was examined by adjusting the heater

Table 3. Experimental parameters

Exp.	Parameters	Run 1	Run 2	Run 3	Run 4
1	Type of helmet	Normal helmet	PCM-cooled helmet	–	–
2	Simulated solar radiation	On	Off	–	–
3	Heater power [W]	6	8	10	–
4	Wind speed [kmh^{-1}]	0	50	70	90
5	Heat exchange with surrounding	Adiabatic condition	Convective condition	–	–

power to three different values: 6, 8, and 10 W. Wind speeds of 0, 50, 70, and 90 km/h were used to study their effects on the PCM cooling system.

Two heat transfer conditions were devised and investigated. Figures 3 and 4 illustrate the two different experimental arrangements. Case A in fig. 3 represents the adiabatic condition where a layer of insulation is used to prevent heat exchange between the heater and the surrounding. Since the heat loss is minimized, all heat generated by heater and heat received from simulated solar radiation should be transferred to the PCM. It is assumed that the heat loss to the polystyrene foam is small and can be ignored. The testing under adiabatic condition is carried out by covering the heater and PCMSU with insulation as well as closing the face shield to prevent air from flowing in the helmet. Case B in fig. 4 represents the convective condition. Without the insulation, convective heat exchange can occur between the heater and surrounding. This should reduce the total heat gained by the PCM compared to the adiabatic condition. For the testing under convective condition, the insulation covering the heater and PCMSU is removed and the face shield is opened.

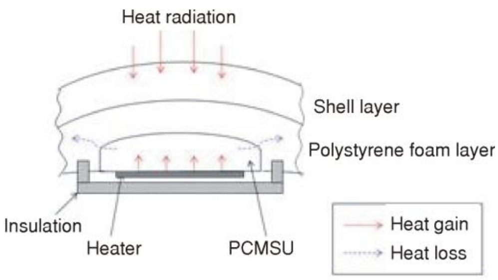

Figure 3. Case A (adiabatic condition)

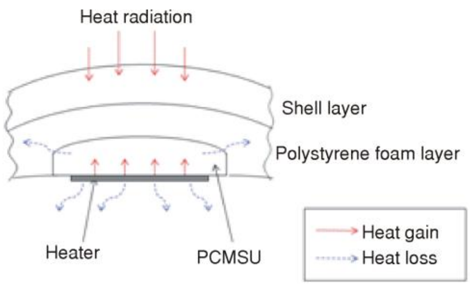

Figure 4. Case B (convective condition)

Results and discussion

Effect of PCM on the helmet interior temperature

Figure 5 compares the PCMSU temperature *vs*. time results between the normal and PCM-cooled helmet (under adiabatic condition) subjected to a constant heater power at 6 W with no wind and the radiator heater switched off. Without PCM, it took about 8 minutes for the temperature to reach 40 °C. Adding 49 cm^3 of PCM extends the time to about 21.5 minutes. The results show that with the use of PCM, the temperature inside the helmet can be maintained at a lower temperature for a longer period of time. The amount of PCM used in the experiment had not been optimized to prolong the cooling time. It is envisaged that the cooling period could be extended by using more PCM. However, more PCM would also increase the weight of the helmet.

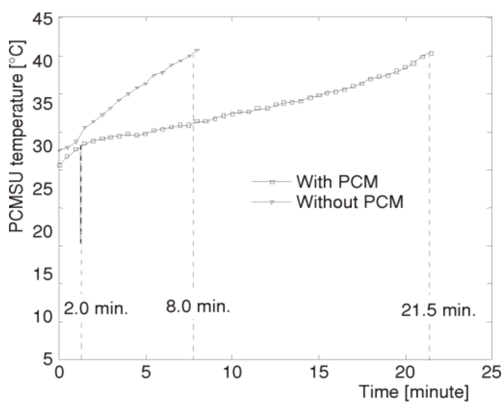

Figure 5. PCMSU temperature *vs.* time – with and without PCM

Effect of heater power on the PCM cooling

Figure 6 compares the PCM temperature *vs.* time performances for different heating powers (under adiabatic condition) with no wind and the radiator switched off. The results for all three heating powers (*i. e.* 6, 8, and 10 W) show that the PCM underwent three distinct stages.

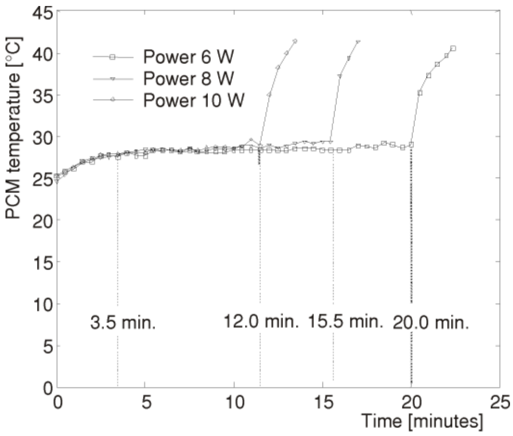

Figure 6. PCM temperature *vs.* time for different heater powers

In stage 1 (*i. e.* the first 3.5 minutes) the initial temperatures of the solid PCM at different heater powers increase at about the same rate from the ambient temperature to the material melting temperature. As more heat is added, stage 1 transforms to stage 2. In stage 2, phase change occurs and latent heat is stored as the solid PCM melts under constant temperature. The PCM temperatures for the three different heating powers remained constant at 28 °C throughout the duration of stage 2. However, the duration of stage 2 is different for the three different heater powers. The time for the PCM to fully melt was about 20 minutes at 6 W. The time for the PCM to fully melt decreases as the heater power is increased. It took about 15.5 minutes and 12.0 minutes for the PCM to fully melt at 8 W and 10 W, respectively. Stage 3 occurs after the PCM has fully melted. In stage 3, sensible heat energy is stored in the liquid PCM and its temperature will increase as heat is continually supplied. Figure 6 shows that the PCM temperatures increased very quickly in stage 3 at the three different heater powers. The results show that any increases in heater power will shorten the PCM melting time. To achieve effective cooling it is important to ensure that the operation of the helmet does not exceed the duration of stage 2. Otherwise, the temperature inside the helmet will rise very quickly. As the duration of stage 2 is dependent on the amount and type of PCM used, the required cooling period could be adjusted by using sufficient amount of appropriate PCM. These factors will be discussed in the section *Design consideration*.

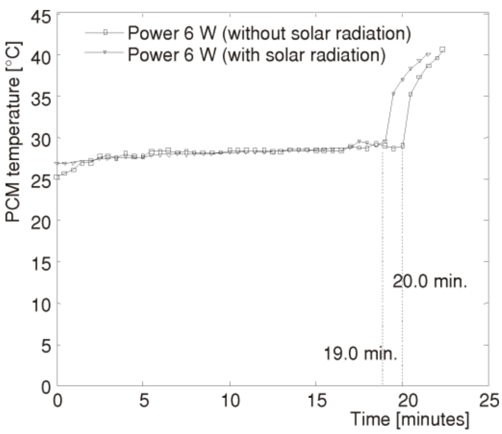

Figure 7. PCM temperature *vs.* time with and without simulated solar radiation

Effect of simulated solar radiation on the PCM cooling

Figure 7 shows the effect of the simulated solar radiation on the PCM temperature *vs.* time profiles (under adiabatic condition) with no wind and the heater at 6 W. The PCM melting time with and without simulated solar radiation are about 19 minutes and 20 minutes, respectively. Although the PCM melting time with simulated solar radiation is slightly shorter than without simulated solar radiation, the difference is very small. This could be attributed to the helmet design. The helmet consists of three main layers: the outer shell, impact absorbing-liner, and comfort padding. The outer shell is made of fiberglass to give the helmet the desirable structural strength. The impact absorbing-liner is made of polypropylene foam and it acts as a cushion to dampen the force during accidents. This layer is about 2.5 to 5 cm thick and is very similar to the thermal insulation used in refrigerators. The function of comfort padding is to provide comfortable contact between the head and helmet. Together these three layers provide the insulation to reduce the heat gained from the radiation. As such, the effect of radiation on the PCM melting time is not significant. This finding is interesting as the three layers will also prevent the dissipation of the heat generated from the head to the helmet outer surface during a cold day.

Effect of wind speed on the PCM cooling

Figure 8 shows PCM temperature *vs.* time profiles for different wind speeds with the radiator switched off and the heater at 6 W. The experiments were performed under adiabatic condition. The PCM melting time did not vary significantly for wind speeds from 0 to 90 km/h. This again can be attributed to the helmet design. Very little heat is conducted across the helmet due to the insulation provided by the three layers mentioned in the previous subsection. Under the adiabatic condition, the use of forced convection on the outer surface to remove the heat within the helmet will not be effective and the wind speed would have very little effect on the PCM melting time.

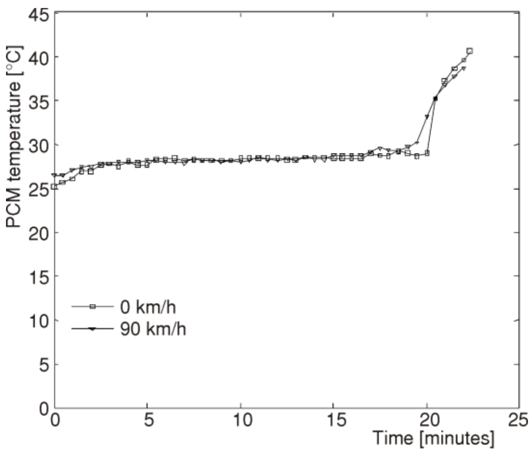

Figure 8. PCM temperature *vs.* time for different wind speeds

Effect of convective condition on the PCM cooling

Figure 9 shows the results of PCM temperature *vs.* time for 10 W heater power with the radiator switched off and under no wind but subjected to the convective condition. The PCM melting time is slightly longer compared to the corresponding adiabatic condition shown in fig. 6. In the adiabatic case, it took about 3.5 minutes for the PCM to reach its melting temperature and the melting time is about 12 minutes. Under the

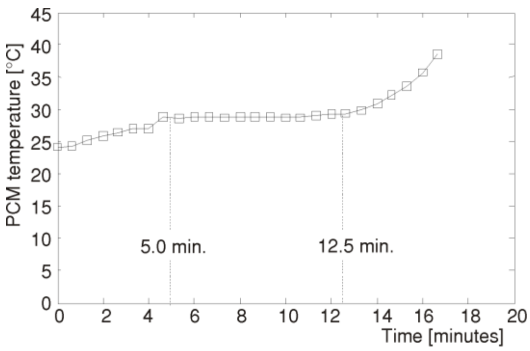

Figure 9. PCM temperature *vs.* time for heater power at 10 W (convective condition)

convective condition (shown in fig. 4), it took about 5 minutes for the PCM to reach its melting temperature and the melting time is about 12.5 minutes. At the end of stage 2, the temperature rise is more gradual under the convective condition. This is attributed to the heat lost to the surrounding via convection. Nevertheless, the amount of this heat loss through convection is small and has very little impact on the performance of the PCM cooling system. Table 4 summarizes the melting time for the different heater powers under adiabatic and convective conditions. The results show that the difference in PCM melting time for both cases is about half minute to one minute. The results indicate that the face shield of the helmet would block the air flowing into the helmet and thus reduce the effectiveness of the convection heat transfer process. Although the impact is small, it helps to explain why motorcyclists prefer to open their face shield while traveling on a hot day.

Table 4. Melting time for adiabatic and convective conditions

Power [W]	Melting time, Δt [minutes]	
	Adiabatic case	Convective case
6	20.0	21.0
8	15.5	16.0
10	12.0	12.5

Design considerations

The experimental findings indicated that the temperature inside the helmet can be maintained within the thermal comfort level for a longer period of time with PCM. The results also showed that the amount of n-octadecane used in the experiments can only maintain the temperature for about 21.5 minutes (under adiabatic condition) when subjected to a 6 W constant heater power with no wind and simulated solar radiation. For practical purposes, the amount of PCM used has to be increased so that the cooling period can be extended. Recommendations based on health and safety suggested that motorists should take periodic rests at least once every two hours when driving long distances. As such, the PCM should be capable of providing continuous cooling for up to two hours.

To extent the cooling period the choice of material is important as the melting time will depend on not only the amount, but also the type of PCM used. There are many types of PCM available in the market and these include organic-based paraffin-based PCM [15], salt hydrates, metallic alloys, and “dry” PCM. Each has its own advantages and disadvantages for the application. For example, paraffin is relatively inexpensive and has high heat storage capacity per unit volume. However, containing liquid paraffin may be a problem. Salt hydrates absorb and loose water during phase change and tend to form partially hydrated crystals, which are generally corrosive. Metallic alloys, with higher latent heat per unit volume than paraffin, have been explored in high-performance military systems [16]. However, the density of metallic alloy would result in relatively heavier helmet. “Dry” PCM [17] includes micro-encapsulated solid-liquid phase change composites and solid-solid organic phase change compounds. They can eliminate liquid containment problems and have good thermal conductivity. However, these materials are expensive and their heat storage capacity per unit volume can be much lower than paraffin. When selecting the PCM for the helmet the operating temperature should also be considered. PCM technology is still evolving and other new organic and composite PCM should be explored in view of these considerations.

The experimental study indicated that the heat generation from the head is the predominant factor that will affect the PCM melting time. Simulated solar radiation and wind speed under adiabatic condition can have very little influences on the PCM melting time. The results suggested that the helmet usage time would depend on the amount of heat generated from the head. In this study, the cooling is concentrated at the top of the head. For practical purposes, it may be desirable to spread the PCM over the interior surface of the helmet so as to extent the cooling to the entire head [18]. One way to distribute the PCM is through pouches in the comfort padding. A rough estimate based on a spherical helmet of internal radius 15 cm with a 1 cm thick layer of PCM distributed over half the sphere suggested that the comfort padding should be able to accommodate about 1500 cm^3 of PCM. The feasibility of using this amount of PCM to extend the cooling to 2 hours at 10 W of heater power would need to be further investigated via numerical studies [19]. In addition, the impact of the increased in helmet weight with the use of more PCM on the user will also have to be further investigated in future studies.

Discharging the heat from the PCM is also a major design concern. When the PCM has 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. To overcome this problem, the ease of removal of the PCM pouches has to be considered. The user should be able to quickly and easily replace the pouches with fresh PCM every 2 hours. The removed liquid PCM can be re-used after discharging the stored heat to the ambient. One way to implement this is to integrate the PCM pouches with the comfort padding in the form of a shower cap. This will facilitate the process as the entire PCM-cap can be easily removed and replaced as and when needed. The removed cap can be soaked in cold tap water to hasten the PCM discharging process. Another advantage of this PCM-cap approach is that it requires no modifications to the helmet. Thus its structural characteristics and aesthetical features will not be affected. The separation of the PCM-cap with the helmet would also allow the cooling system to be used in a variety of head protection devices.

The efficiency of the heat transfer from the head to the PCM is another important design consideration in the future development of the PCM-cooled helmet. The heat transfer could be enhanced by using thin flexible aluminum foil to contain the PCM. Fok *et al*. [20] suggested that the internal fins could improve the PCM heat transfer process. This could be implemented using thin wire mesh or honey-combed structure within the PCM enclosure. Honeycomb sandwich structures have good relative stiffness and strength to weight ratio. These structures also have good crush resistance and energy absorption properties, which could further lessen the impact force during accidents [21].

Conclusions

The influences of the simulated solar radiation, wind speed, and heat generation rate on the PCM cooling for a motorcycle helmet have been investigated through several experiments. The results show that with the use of the PCM-cooling system, the temperature inside the helmet will take a longer time to exceed the thermal comfort zone compared to a normal helmet. The findings also show that higher head heat generation rate will shorten the PCM melting time. This is the main factor affecting the cooling system performance. Simulated solar radiation and wind speeds do not have much impact on PCM melting time under adiabatic condition. Some major design considerations based on these influences have been discussed. Although the investigation in this work focuses on the cooling of a motorcyclist helmet, the findings could also be useful for the development of PCM-cooling systems in other applications.

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