Original Article

Increased Thermal Comfort of Motorcycle Helmet Users with the Addition of Phase Change Material

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Abstract

Aim: The aim of this paper is to design a helmet that can absorb heat from the scalp with phase change material (PCM) made from polyethylene glycol (PEG) 6000. The helmet design in the form of a three-dimensional computer-aided design model is made based on existing conditions and modified conditions with the addition of PCM. **Methods:** Simulation of heat propagation in a helmet using the finite element analysis (FEA) method was used to determine the effectiveness of the amount of heat that can be absorbed from the rider's scalp. There were two types of PCM housing (pouch) that were tested, namely pouch – 2 mm thick aluminum (Al) plate and linen flax type fabric. **Results:** Based on the FEA simulation results, pouches made from flax linen are able to improve heat absorption on the scalp in contact with the helmet foam from a predicted mean vote (PMV) = 3.5 (hot) with a Predicted Percentage of Dissatisfied PPD = 100% to a PMV of 1.1 (slightly warm) with a PPD = 31.9%. **Conclusions:** It can be concluded that PCM with PEG 6000 powder can significantly improve the thermal comfort of helmet wearers. The potential for innovation in PCM pouch materials is still wide open for future research.

Keywords: Finite element analysis, helmet, phase change material, polyethylene glycol 6000, predicted mean vote

Introduction

Global traffic accidents are still very high, including those that occur in developing countries such as Indonesia. The still high level of traffic accidents is caused by many factors, such as poor road infrastructure, incomplete traffic infrastructure, and driving behavior that causes human error. Bad driving behavior can be caused by many factors, including low skills, uncontrolled emotions, hot weather, driving culture, and the driver's psychological health.[1] Environmental climate conditions, such as wind, heat, humidity, and rain, greatly influence driving behavior, especially on two-wheeled motorbikes. Exposure to heat on the driver's body and head will directly affect brain performance, which will be coordinated through levels of anxiety, stress, and concentration while driving.[2,3] Riders wearing a helmet can cause the head temperature to rise from 37°C to 38°C.[4] The local thermal sensation that occurs in the rider's head will dominate the thermal sensation throughout the body.[5]

There have been many motorbike helmet designs that try to reduce temperature, which in turn can increase the rider's thermal comfort level. Tiest and friends explain in their book how sustainable textile materials such as PCMs reduce heat stress in motorcycle helmets.[6] The use of phase change materials (PCMs) is very effective because it does not require an external energy source, is silent and does not add significantly to the weight of the helmet. Helmet cooling with PCM is widely considered an inexpensive, compact, reliable, and simple solution to implement.[7] This paper will test the effectiveness of a new PCM material, namely polyethylene glycol (PEG) 6000, to absorb heat in motorbike riders' helmets. PEG 6000 is a powder material that is light and remains dry because it does not melt, is biodegradable and nontoxic. This material is an alternative solution to previously developed PCM

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materials, such as textile, Nextek 28D, Paraffins, hydrated salts, and microencapsulated.[8-11]

Materials and Methods

When exercising in a hot environment, convection heat transfer occurs, at which time heat loss from the head is estimated at 200–250 W. Heat loss from the head is a quarter to a third of the total heat output from the body's metabolism as a whole.[12,13] This is substantially higher than the head's proportion (7%–10%) of total body surface area. Cooling the head with a lid and running cold water can remove 30% of the metabolic heat produced at rest and 19% during exercise at 50% of maximum oxygen uptake. This may indicate the importance of the head as a heat sink. Thus, the head has a fairly large heat loss capacity.

Predicted mean vote (PMV) is an index used to predict the overall thermal sensation felt by people in a large group. The PMV model shows that thermal sensation can be described as a function of the thermal load on the effector mechanisms of the human thermoregulatory system. The PMV value determines the range of temperature sensations that people feel in the surrounding environment. This PMV index ranges from −3 (very cold) to +3 (very hot).[14,15] predicted percentage of dissatisfied (PPD) is a derivative of PMV that predicts the percentage of people who are thermally dissatisfied. Once the PMV value is known, the PPD value can be calculated using Equation (1)

$$PPD = 100 - 95 \times e^{-(0{,}03353 \times PMV^4 + 0{,}2179 \times PMV^2)} \quad (1)$$

The four main parts of a motorcycle helmet are the outer shell, energy-absorbing layer, comfort layer, and retention system [Figure 1]. The main function of the outer shell is to distribute the impact load over the largest possible area and to protect the head from penetration by sharp objects.[16] There are basically two types of shells: thermoplastic shells and composite shells.[17] Composite shells are usually made of fiber-reinforced plastic. The most commonly used type of reinforcement is glass; carbon fiber and Kevlar are also used. Composites are characterized by excellent mechanical properties and low weight, but their high cost justifies their use only for the most advanced helmets.

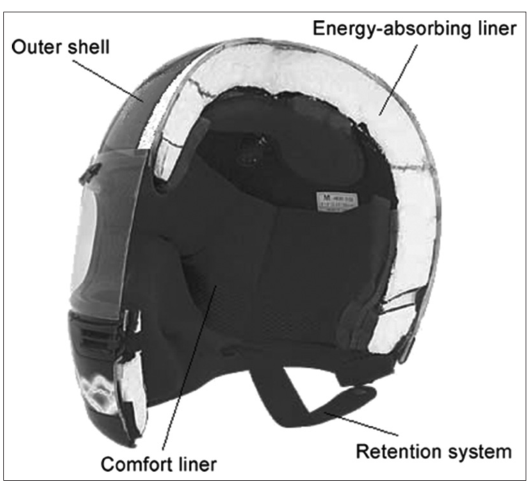

Figure 1: The main components of helmet materials

PCMs are substances with high latent heat that are capable of storing and releasing large amounts of energy when melted and solidified at certain temperatures.[18] PEG, which has a molecular weight of 6000 (PEG 6000), is used as a PCM with a melting range suitable for thermal comfort in buildings. PEG 6000 has a melting point of 62.1°C, crystallization temperature of 42.5°C, heat of fusion = 177.9 kj/kg, thermal conductivity = 0.34 W/mK, specific capacity = 8996 kj/mol K, and density = 1200 kg/m^3.[19] PEG 6000 has stable thermal properties over a number of repeated uses, which is advantageous for being used as a heat-absorbing material in helmets.

Ethical approval

Ethical approval for this study (Ethical Committee UB 2024) was provided by the Ethical Committee UB of Brawijaya University.

Research methodology

The research design used a simulation of the finite element analysis (FEA) method on a three-dimensional computer-aided design (3D CAD) model of a helmet that is made according to its shape, size, and constituent materials. FEA simulation is used to determine the distribution of heat from the scalp to the helmet material. The simulation was carried out to compare the effectiveness of the PCM material in absorbing heat originating from the rider's scalp. The research steps taken include:

1. Create a solid 3D CAD model of a motorbike helmet
2. Measure the melting point of PEG 6000 with 3 measurements
3. Compare the cooling speed between 2 mm aluminum plates treated with 7 g of PEG 6000 and those without PCM
4. Carry out an FEA simulation to determine heat propagation and the effectiveness of adding PEG 6000 in heat absorption. The PEG 6000 pouch design/house is made from a 2 mm thick aluminum (Al) sheet with dimensions = 22 cm × 15 cm × 1.35 cm
5. Carry out an FEA simulation to determine heat propagation and the effectiveness of adding PEG 6000 in heat absorption. Pouch design/home PEG 6000 is made from linen flax fabric
6. Analysis and discussion of the effectiveness of PCM with PEG 6000 powder and with a pouch made from flax linen in providing thermal comfort for riders
7. Thermal comfort can be described in terms of changes in the PMV value toward zero (neutral) and a decrease in the PPD value.

Results

The research began with a survey of motorbike riders' complaints due to heat exposure from wearing helmets. Respondents were taken numbering more than 70 people and taken, randomly from drivers who were in hot areas, such as in the cities of Surabaya, Gresik, Tuban, and others. From the survey results, it was found that respondents who drove in hot areas stated that 100% felt heat stress with the majority, around 82%, stating that it was difficult for them to concentrate properly when riding a motorbike. Therefore, it is very important to be able to relieve heat stress from using a helmet.

Based on experimental results, the use of 7 g of PEG 6000 is very effective for cooling 2 mm aluminum plates with a homogeneous heat temperature of 450°C and room temperature of 250°C. The plate temperature changes at several points were recorded using a thermal imaging camera [Figure 2a]. Meanwhile, Figure 2b shows the decrease in temperature on the aluminum plate due to the addition of PEG 6000. From the graph, it can be explained that the addition of PEG 6000 can significantly absorb the surrounding heat, where in the first 60 s of data recording, the plate temperature dropped from 450°C to 35.20°C. This is different if the plate is not given PCM, namely it only drops around 50°C from 450°C to 400°C. This shows that PCM PEG 6000 and aluminum can be relied on to reduce heat stress in motorbike helmets.

The first step before the FEA simulation is to create a 3D helmet design using CAD software. In this step, the 3D design is divided into 2 components, namely the full-face helmet and the PCM holder. The full-face helmet design can be seen in Figure 3 which has outer dimensions of 268.5 mm × 248.42 mm × 271.79 mm. In the Styrofoam layer of the helmet, there is space to place a PCM pouch measuring 82.4 mm × 102.4 mm × 11.4 mm. The thickness of the aluminum wall where the PCM is used is 1.2 mm. The Al pouch functions as a place-to-place PEG 6000 as well as a heat collection medium in the helmet, and then the heat will be absorbed by the PEG 6000.

In the first stage of the simulation, the existing pouch shape made from aluminum was used to test the effectiveness of PCM PEG 6000 on 3 CAD helmet models. Figure 4a explains the results of the FEA simulation of heat distribution in helmet components starting from foam, Styrofoam, and the outer shell of the helmet for existing conditions (without PCM). Based on the picture, it can be explained that the heat from the foam surface in contact with the scalp is not distributed well to the outside of the helmet, resulting in excessive heat felt by the rider. The average heat generated for the middle part of the foam is 40.70°C, the middle part (Styrofoam) has a heat of around 32.50°C, and the skin part has an average of 25.7°C. The thermal comfort value for riders wearing existing helmets can be measured using the PMV and PPD methods. Based on input data for room temperature of 25°C, scalp temperature of 45°C, isolation (Icl) of 0.71 clo, relative humidity = 85%, wind speed of 0 m/s, and metabolism of 1 Met, the PMV value is 3.5 (heat) with PPD = 100% (formula 1). This shows that if the contact temperature between the scalp and the helmet foam on a helmet without PCM is 45°C, then 100% of all riders will feel very hot.

Figure 4b shows the FEA simulation results for heat distribution from contact of the scalp with helmet foam at a heat input of 45°C. If compared with Figure 2a, it is

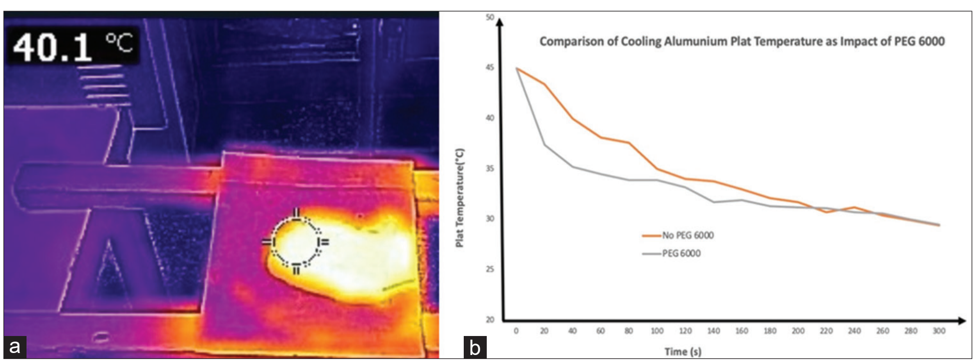

Figure 2: (a) Process of collecting plate cooling data with and without phase change material polyethylene glycol (PEG) 6000, (b) graph of temperature reduction for aluminum plates due to PEG 6000. PEG: Polyethylene glycol

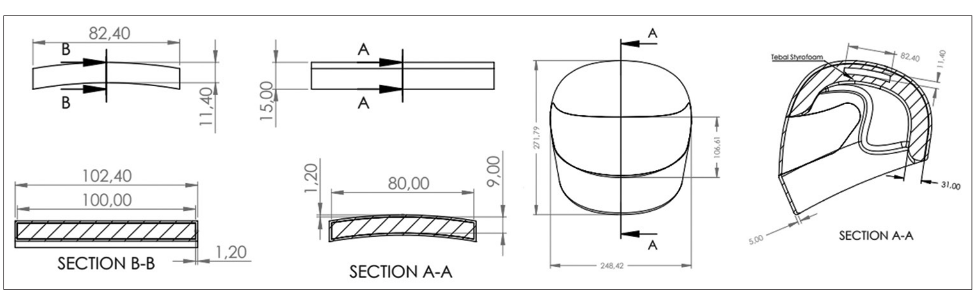

Figure 3: Phase change material (PCM) shape and dimensions and PCM location in the helmet; A-A for Side section, B-B for front section

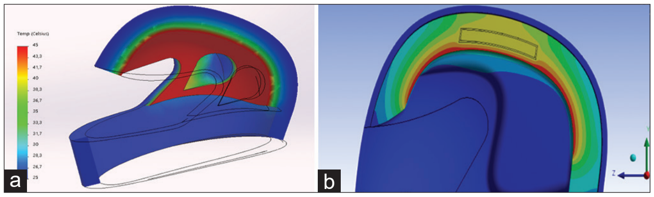

Figure 4: (a) Simulation of heat propagation to the scalp at 45°C for helmets without phase change material (PCM), (b) simulation with PCM polyethylene glycol 6000 with pouch made from aluminum

very clear that the heat originating from the surface of the helmet will be distributed around the PCM PEG 6000 with an aluminum housing/pouch collector. The average heat generated for the middle part of the foam is 37.40°C; the middle part (Styrofoam) has a heat of around 37.60°C; and the skin part has an average of 26.1°C. Based on the same conditions as existing, changes in temperature around the scalp will reduce the heat felt by the driver's scalp, with a PMV value of 0.4 and a PPD of 8.5%. These results show that PEG 6000 is very effective in absorbing heat with thermal comfort conditions that can be accepted by all helmet Wearers (PPD <10).

The amount of heat absorbed by PEG 6000 with AL pouch (1.2 mm thick) is as Equation 2:

$$Q = \mathrm{m}\ x\ c\ x\ \Delta t \qquad (2)$$

Q = 0,087 x 1499,33 x (37.6-25)= 1643.5 J =3.93 Kcal.

Discussion

As explained at the beginning, the use of metal materials is not permitted by law in Indonesia through SNI1811-2007. An alternative PCM housing for PEG 6000 powder must be sought that is elastic or a material that does not aggravate deformation when an impact occurs on the helmet, but is capable of being a good heat conductor or has high thermal conductivity. The material in the form of linen flax fabric is a good alternative for simulating thermal distribution in its function as a container for PEG 6000 powder. Based on the simulation results, it was found that the average heat generated for the middle part of the foam was 39.30°C, the middle part (Styrofoam) had heat around 35.60°C, and the skin had an average of 25.4. Based on the same conditions as existing, changes in temperature around the scalp will reduce the heat felt by the driver's scalp, with a PMV value of 1.1 (slightly warm) and a PPD = 31.9%. These results show that a total of 31.9% of helmet users will still feel uncomfortable due to the heat of wearing a helmet.

In the future, it is necessary to continue searching for materials that are safe and nonmetallic to reduce the percentage value of PPD due to the use of PCM in helmets. Fabric materials such as Faraday 245 can be an alternative to produce better heat absorption of PEG 6000, because they also have better conductivity values. It is very important that the addition of a PCM component to a motorbike helmet is a change in the strength of the helmet in an effort to protect the rider. Increasing the driver's thermal comfort must also pay attention to the user's safety. The future research steps need to test the impact of impacts on helmets that are added with PCM PEG 6000 material and its wrapping made of linen flax fabric. This testing will make it possible to change the dimensions and shape of the motorcycle helmet.

Conclusions

Thermal comfort on a motorbike rider's head plays an important role in improving driving safety. The heat stress that occurs can cause loss of concentration or even lead to poor driving behavior. Heat stress can be made worse by wearing a helmet, so helmet innovation is needed that can control the heat that occurs. The addition of a heat sink component in the form of PCM made from PEG 6000 is able to significantly reduce temperature by absorbing heat. The use of PEG 6000 placed in a heat collector made from Lenin flax fabric can be explained well through FEA simulations. With PEG 6000 material, which is classified as stable in its physical properties over a long usage cycle and is also classified as a safe substance for the human body, the potential for future development will be increasingly wide open.

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Conflicts of interest

There are no conflicts of interest.

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