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HEAT PIPE AND GRAPHENE-ENHANCED PCM APPROACH FOR ELECTRIC BATTERY THERMAL MANAGEMENT SYSTEM

RAHMAT IMAN MAINIL[1], FADILLAH MUHADDASIEN MAUFI[2],
JULIUS MANATAR SIBURIAN[3], AFDHAL KURNIAWAN MAINIL[4], AZRIDJAL AZIZ[5]

Abstract

As electric vehicles (EVs) gain popularity, maintaining optimal battery temperature is crucial for enhancing performance, extending lifespan, and ensuring safety. This study investigates the integration of heat pipes, which facilitate efficient heat transfer, and phase change materials (PCM) that absorb and release thermal energy during phase transitions, providing a dual approach to thermal regulation. The addition of graphene to PCM is objected to improve thermal conductivity and heat dissipation of the system. The proposed system facilitates rapid heat transfer through heat pipes and leverages the high latent heat storage capacity of PCMs and superior thermal conductivity of graphene to effectively regulate the battery temperature. The performance of heat pipe and PCM with graphene combination (7%, 15%, and 30% m/m) on battery were simulated in an experimental simulation system uder heat load of 22 W, 44 W and 66 W. As a result, integrating graphene into the PCM matrix significantly improves the paraffin wax thermal conductivity, leading to reduced peak battery temperatures under all tested heat loads. Among the tested systems, the one with 30% (m/m) graphene consistently delivered the most effective cooling, maintaining the lowest temperatures at each heat input. However, at the highest heat load (66 W), the temperature difference between the systems with

[1] Mechanical Engineering, Thermal Engineering Laboratory, Universitas Riau HR. Soebrantas Km. 12,5, 28293, Pekanbaru, Indonesia, email: rahmat.iman@lecturer.unri.ac.id, ORCID: 0000-0002-2720-5386

[2] Mechanical Engineering, Thermal Engineering Laboratory, Universitas Riau HR. Soebrantas Km. 12,5, 28293, Pekanbaru, Indonesia, email: fadilmaufi@gmail.com, ORCID: 0009-0003-8421-2819

[3] Mechanical Engineering, Universitas Riau HR. Soebrantas Km. 12,5, 28293, Pekanbaru, Indonesia, email: juliussiburian19@gmail.com, ORCID: 0009-0001-3695-4776

[4] Mechanical Engineering, Universitas Bengkulu Bengkulu, Indonesia, email: mainilafdhalk@unib.ac.id, ORCID: 0000-0001-5455-9879

[5] Mechanical Engineering, Thermal Engineering Laboratory, Universitas Riau HR. Soebrantas Km. 12,5, 28293, Pekanbaru, Indonesia, email: azridjal.aziz@lecturer.unri.ac.id, ORCID: 0000-0002-8601-7107

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15% (m/m) and 30% (m/m) graphene was minimal, indicating a potential saturation point in the thermal performance benefits. The findings indicate that the hybrid approach of using heat pipes combined with graphene enhanced PCM offers a promising solution to effectively manage battery thermal dynamics, ultimately contributing to the advancement of electric vehicle technology.

Keywords: Passive Cooling; Thermal Management; Heat Pipe; Graphene-Enhanced PCM; Electric Vehicle Batteries; Phase Change Material

1. Introduction

Concerns about the future of the earth and humanity are widespread due to the rising of global temperatures, climate change, and increasing greenhouse gas emissions [1, 2]. Industrial and transportation sector, which rely heavily on fossil fuels for energy, are major contributors to these issues [2]. In the land transportation sector, internal combustion engines that run on oil-based fuels remain the primary technology used today. This has led to a persistent environmental pollution issue. To mitigate emissions from land transportation, the development of electric vehicles has accelerated globally. Therefore, electric vehicles (EVs) have the potential to be a key solution in reducing greenhouse gas emissions while also improving air quality.

The growing adoption of electric vehicles is largely driven by advancements in lithium-ion battery (LIB) technology, which delivers efficient and high-energy-density power for vehicle propulsion. LIBs offer several key advantages, including high current output, superior power and energy density, a long lifespan, no memory effect, and a low self-discharge rate, making them an ideal choice for modern electric vehicles. Despite their many advantages, LIBs are highly sensitive to temperature, especially in high-current applications and varying ambient conditions. Excessive heat generation can lead to overheating, which negatively affects performance, triggers exothermic reactions, and can cause fires or explosions in extreme cases [3–5]. To preserve the battery's essential characteristics, which are crucial for a sustainable electric vehicle, its temperature should be maintained between 25°C and 55°C.

There are various techniques that have been developed to maintain the temperature of the LIB to prevent overheating, namely air cooling [6, 7], liquid cooling [8], phase change cooling [9, 10], and heat pipes [11].

The air cooling approach is straightforward, cost-effective, and easy to apply. Key factors that influence the performance of an air-based battery thermal management system (BTMS) include airflow characteristics, battery arrangement, and the dimensions of the cooling channels. However, although air-based BTMS performs well overall, it faces several

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challenges such as a low heat transfer coefficient, limited thermal conductivity, significant parasitic power consumption, noise generation, and pressure drops [12]. These issues become more pronounced in modules containing a large number of lithium-ion batteries operating at high currents, often resulting in uneven temperature distribution.

Compared to air-based systems, liquid-based BTMS offers more effective cooling due to the high specific heat capacity of liquid coolants [13]. Mini-channel cooling systems have shown promise in managing the heat produced by lithium-ion batteries. However, challenges such as the volume and weight of the coolant, potential leakage, higher costs, and pressure drops limit the practicality of this approach [14]. To address these drawbacks, phase change material (PCM) technology has been integrated into BTMS designs to absorb and dissipate heat through solid-to-liquid transitions. While PCM is affordable and relatively simple to implement in hybrid electric vehicles, its low thermal conductivity, limited heat capacity, potential for leakage in the liquid state, thermal instability, and additional space and power demands can reduce overall cooling effectiveness [15].

Heat pipes have emerged as an effective passive cooling solution, offering high thermal conductivity, cost efficiency, lightweight design, and long operational life. The battery of an electric vehicle has been cooled by I shape heat pipe as reported by Mbulu et al [16]. They reported that the design of BTMS heat pipe could transfer more than 92.18% of heat generated.

Several researchers have combined heatpipe and PCM cooling system to enhance the BTMS performance. Wang et al [17] evaluate the cooling performance of cylindrical battery immersed in paraffin. They found that up to 5°C of battery temperature reduce, and battery temperature was maintained below 50°C [18]. Huang et al [18] experimented thermal management system of EV battery with flat heat pipe assisted PCM. They investigated performance of cooling system for pure PCM, heat pipe coupled with air assisted PCM (PCM/HP-Air), and heat pipe coupled with liquid assisted PCM (PCM/HP-Liquid), respectively. Their findings indicated that the heat pipe was highly effective in rapidly transferring heat within the PCM-based battery module. Furthermore, the integration of the heat pipe with the phase change material (PCM) significantly enhanced the thermal management system's overall performance. Putra et al [19] investigate the performance of bess wax PCM with heat pipe for passsive cooling of EV's battery. They found that the maximum temperature decrease from EV's battery was 33.42°C. A summary of BTMS using HP and PCM as cooling methods, along with their improvement potential, is presented in Table 1.

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Tab. 1. Researches on BTMS using HP and PCM as cooling methods

Research	Colling method	Experimental condition	Results	Improvement potential
Mbulu et al. (2021) [16]	HP, water cooling	The system was tested under heat inputs of 30 W, 40 W, and 50 W, with cooling water flow rates at the HP condenser set to 0.0167 kg/s, 0.0333 kg/s, and 0.05 kg/s.	Under maximum input power, the battery temperature can be effectively controlled below 55°C.	The potential use of air as a cooling medium for the HP condenser should be evaluated, as air cooling is generally more practical and easier to implement in real-world applications.
Wafirulhadi et al. (2021) [20]	HP + PCM (soy wax), air cooling	A simple setup was tested under four conditions: no cooling, PCM cooling, heat pipe cooling, and combined PCM-heat pipe cooling.	The combination of HP and PCM reduced the battery temperature by more than 50°C, from 108.2°C to 58.3°C.	The heat transfer performance of soy wax can be enhanced by integrating additives with superior thermal conductivity.
Huang et al. (2018) [18]	Plate HP + PCM (paraffin), air cooling	They investigated performance of cooling system for pure PCM, heat pipe coupled with air assisted PCM (PCM/HP-Air), and heat pipe coupled with liquid assisted PCM (PCM/HP-Liquid),	The heat pipe was highly effective in rapidly transferring heat within the PCM-based battery module.	Due to its low thermal conductivity, paraffin can be combined with high-conductivity materials to achieve better battery temperature control.
Putra et al. (2020) [19]	HP + PCM (besswax)	Heat inputs of 40 W, 50 W, and 60 W. Three cooling systems was employed and compared (without HP, with HP, and with HP + PCM)	At a 60 W heat load, the heat pipe reduced battery temperature by 26.62°C compared to the case without passive cooling, while the addition of PCM further enhanced the temperature reduction.	Beeswax melts at 62.28°C, which exceeds the recommended battery operating range; hence, selecting a PCM with a melting point within this range is more advantageous.

Since certain PCMs, such as paraffin wax, possess low thermal conductivity, incorporating high-conductivity materials is essential to improve heat absorption. Wu et al. [21] demonstrated this approach by embedding a porous copper sheet into paraffin, which increased its thermal conductivity from 0.26 W/m·K to 7.65 W/m·K and lowered the battery surface temperature by 3.9°C.

In this study, the addition of graphene powder into paraffin wax PCM is developed to enhance the thermal conductivity of PCM. The cooling performance of straight heat pipes with graphene enhanced-PCM were compared with heat pipes with PCM without graphene. Amount of graphene were varied to obtain the optimum cooling performance of BTMS. To our knowledge, research on the effect of graphene addition to PCM on heat pipe and PCM battery cooling system has not been reported before. Therefore, this study will evaluate the effect of graphene addition on battery cooling performance of heat pipe and PCM cooling system.

2. Materials and Methods

The installation of the EV battery cooling systems was designed by the integration of heat pipe and PCM. The experimental apparatus was equipped of two battery simulators made of stainless steel with a heater, two straight heat pipes, and PCM container. The battery simulators have dimension of 135 mm x 80 mm x 30 mm. A heater was installed inside each battery simulator to replicate the heat generation of a real lithium-ion battery. A Voltage regulator was used to regulate heat load in the battery simulator. Two grooved aluminum plate was placed between the battery, which functions as both a heat pipe holder and a PCM storage area, as shown in the Figure 1. The Fourier heat conduction equation can be used to estimate the heat transferred through a heat pipe based on the temperature distribution across the plate.

The battery simulator pack was placed inside an air duct to replicate the cooling process of Ev's battery. Heat generated by the heaters increased the battery temperature, which was then regulated using a combination of heat pipes and PCM. The heat pipes were specifically utilized to enhance heat transfer due to their high thermal conductivity, ensuring efficient cooling and temperature control.

The heat generated is absorbed by both the PCM and the heat pipe, then dissipated through airflow inside the ducting, driven by a fan. The heat pipe's efficiency is achieved through phase change heat transfer at low pressure, where heat moves from the evaporator to the condenser. At the condenser, the released heat causes the working fluid to condense back into a liquid, which then returns to the evaporator. This cycle repeats continuously during heat pipe operation, ensuring effective heat dissipation. The PCM efficiently stores thermal energy by utilizing both sensible and latent heat. To regulate battery temperature, the key approach is to swiftly dissipate heat from the battery to the environment through a heat pipe while the PCM simultaneously absorbs the excess heat. This combined system improves cooling efficiency and ensures the battery operates within an optimal temperature range.

The heat pipes used in this setup were copper straight pipes with a sintered wick structure, diameter of 3/8 inch filled with water as the working fluid, with a 30% filling ratio. The pipe was installed in a horizontal orientation to minimize gravitational effects. Their specific geometry and dimensions are shown in Figure 2. To enhance heat dissipation, fins were added to the condenser section, increasing the total contact area and improving convective heat transfer between the heat pipe and the airflow inside ducting. The evaporator end of the heat pipe was embedded in the PCM/PCM + graphene composite matrix, ensuring direct thermal contact with the simulated battery surface. Forced convection cooling was applied

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using a controlled airflow generated by an axial fan, delivering a velocity of 2 m/s across the condenser surface to maintain consistent heat rejection conditions.The efficiency of a heat pipe largely depends on its properties, such as thermal resistance.

A heat pipe with lower thermal resistance offers superior performance by facilitating rapid heat transfer. The thermal resistance (Rhp) can be determined by measuring the temperature difference between the evaporator (T_{evap}) and condenser T_{cond} and calculating the heat transferred (Q_{in}) through the heat pipe as indicated at Eq. 1:

$$Rhp = \frac{T_{cond} - T_{evap}}{Q_{in}} \tag{1}$$

In this study, the paraffin wax was used as PCM which melts within the desired operating temperature range of the battery [22]. Paraffin is widely used as a PCM owing to its high latent heat (180–210 kJ/kg) and moderate specific heat (2.1–2.4 kJ/kg·K), but its low thermal conductivity (0.20–0.30 W/m·K) limits heat transfer under high loads. A total of 20 g of paraffin wax was added to the battery system. To ensure uniform distribution, the paraffin wax was first heated to its melting point, allowing it to flow and evenly coat the battery box. As the battery generated heat, the paraffin wax absorbed it, causing an increase in temperature and initiating the phase change process.

To further enhance the thermal performance of the phase change material (PCM), graphene nanoparticles were added to the paraffin wax. Graphene is known for its exceptionally high thermal conductivity, often exceeding 5000 W/m·K, which makes it an ideal additive for improving heat transfer in low-conductivity materials like paraffin. Dispersing graphene into paraffin significantly enhances thermal conductivity while retaining most of its latent heat. Balan et al. [23] reported an increase from 0.2 W/m·K to 0.5 W/m·K with latent heat above 150 kJ/kg at 10% (m/m) graphene.

In this study, graphene nanoparticles were uniformly dispersed within the melted paraffin wax using a high-shear mixing process to ensure even distribution and prevent agglomeration. This mixture was then poured into the PCM chamber of the battery simulator system. Once cooled, the graphene-enhanced PCM solidified into a stable, composite thermal medium capable of absorbing and conducting heat more efficiently than pure paraffin. The integration of graphene-modified PCM ensures a synergistic effect when combined with heat pipes. While heat pipes provide rapid heat transport from high-temperature zones, the graphene-enhanced PCM ensures that the heat is efficiently stored and redistributed, maintaining a stable thermal environment around the battery cells.

K type thermocouples were used to measure battery, heat pipes, and PCM temperatures. The thermocouples were attached at surface center of battery simulator, PCM, and heat pipes to record temperature with digital thermometer Lutron TM TM946 with accuracy of -199.9°C to 850°C and resolution of 0.1°C. The detail of experimental apparatus is illustrated at Figure 1.

https://doi.org/10.14669/AM/215079

The heat energy of battery simulator was controlled by a voltage regulator. The heat generation was controlled at 22 W, 44 W, and 66 W. The air velocity was set at constant flowrate of 2 m/s driven by a fan. An annemometer Benetech GM 802 with accuracy of ± 3% ± 0.1 dgts and resulution of 0.1 m/s was used to measure the air flowrate. The detail of instrumentation is shown in Table 2.

To begin the experiment the battery simulator, the battery simulator was initially operated for 210 minutes without a heat pipe or PCM to establish its maximum temperature. Secondly, the heat pipes were installed on the battery simulators, and the temperature was measured to evaluate their impact on battery cooling. After that, the heat pipes were enclosed with PCM to function as a passive cooling system. Next, graphene powder with variation of mas 7%, 15%, and 30% (m/m) was added to PCM. The temperature of battery simulator was varied by adding heat loads of 22 W, 44 W, 66 W for 210 minutes for all experimental runs.

The BTMS experiments employing HP and PCM cooling are constrained by fixed thermal conditions, the lack of dynamic load testing, the use of a battery simulator rather than an actual battery, and the omission of material and weight cost assessments.

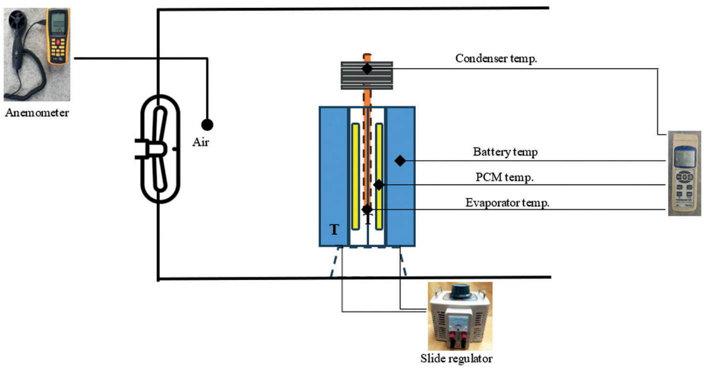


Fig. 1. Experimental Apparatus

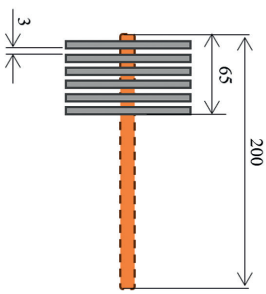


Fig. 2. Heat pipe configuration (size in mm)

https://doi.org/10.14669/AM/215079

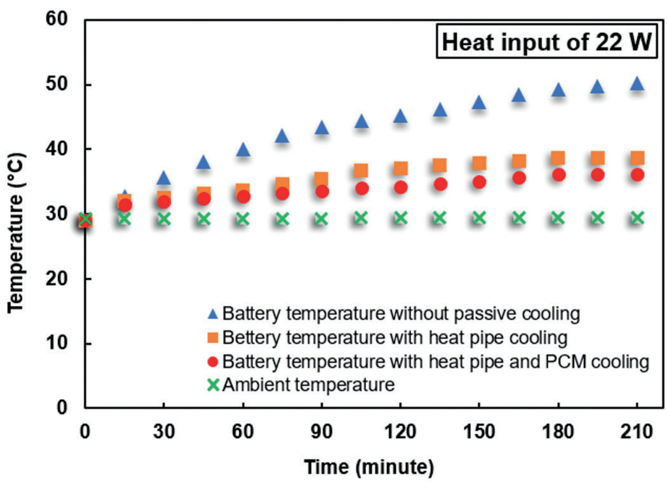
Tab. 2. Detail of instrumentation

Variable	Instrumentation	Measurement accuracy	Resolution
Temperature (°C)	Lutron TM 946	−199.9°C to 850°C	0.1°C
Wind Speed (m/s)	Benetech GM 802	± 3% ± 0.1 dgts	0.1 m/s, 0.2°C

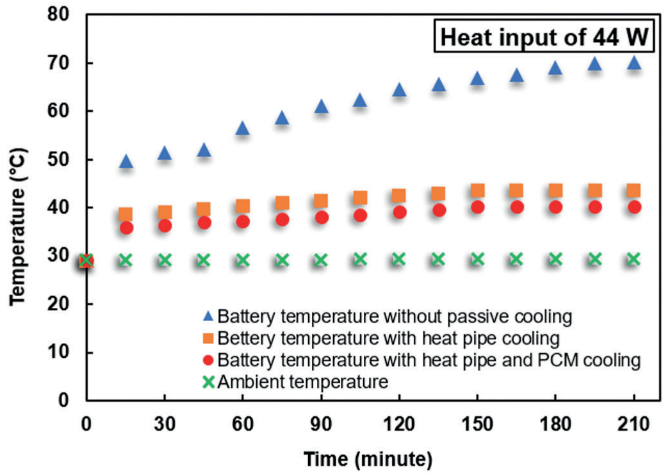
3. Results

3.1. Cooling performance of heat pipe and PCM-integrated heat pipe in EV batteries

Figure 3 presents the comparative battery surface temperature profiles of without passive cooling, with heat pipe cooling, and with heat pipe and PCM cooling at different heat load.



(a)



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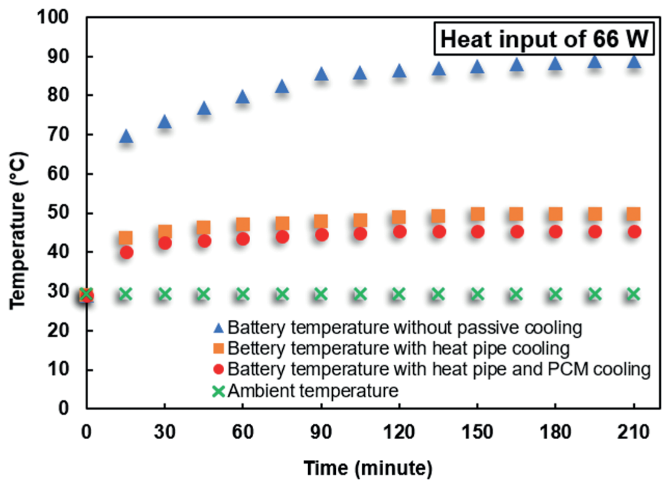


(c)

Fig. 3. Battery surface temperature profiles with different cooling method at different heat load (a) 22 W, (b) 44 W, (c) 66 W

In the absence of heat pipes or PCM, the battery simulator requires a significantly longer time to reach thermal steady-state (temperature of the battery simulator stops changing significantly with time), requiring more than 210 minutes to stabilize under all heat load experimental conditions. However, the integration of heat pipes drastically improves the thermal response, enabling the battery temperature to stabilize at approximately 180 minute, 150 minute, and 150 minute at heat input of 22 W, 44 W, and 66 W respectively. The combination of heat

https://doi.org/10.14669/AM/215079

pipe and PCM accelerate the stabilization of battery temperature for 165 minute, 135 minute, and 120 minute with heat load of 22 W, 44 W, and 66 W respectively. The maximum battery surface temperatures observed without heat pipes and PCM were 50.2°C, 70.2°C, and 89.0°C for heating powers of 22 W, 44 W, and 66 W, respectively. With the inclusion of heat pipes, these temperatures were reduced by 11.6°C, 26.6°C, and 39.2°C, respectively. These temperatures even more lower by 2.5°C, 3.5°C and 4.5°C when paraffin wax was applied.

As shown in Figure 4, the combination of heat pipe and paraffin wax achieved a notable reduction in battery surface temperatures compared to using the heat pipe alone. These results demonstrate that the paraffin wax effectively enhanced the heat absorption capacity of the system.

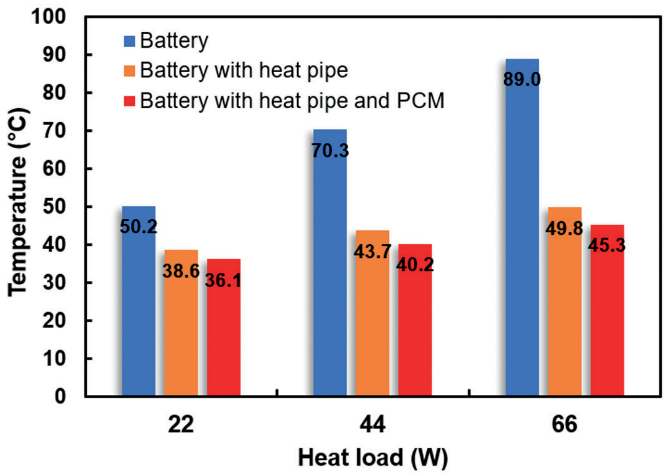


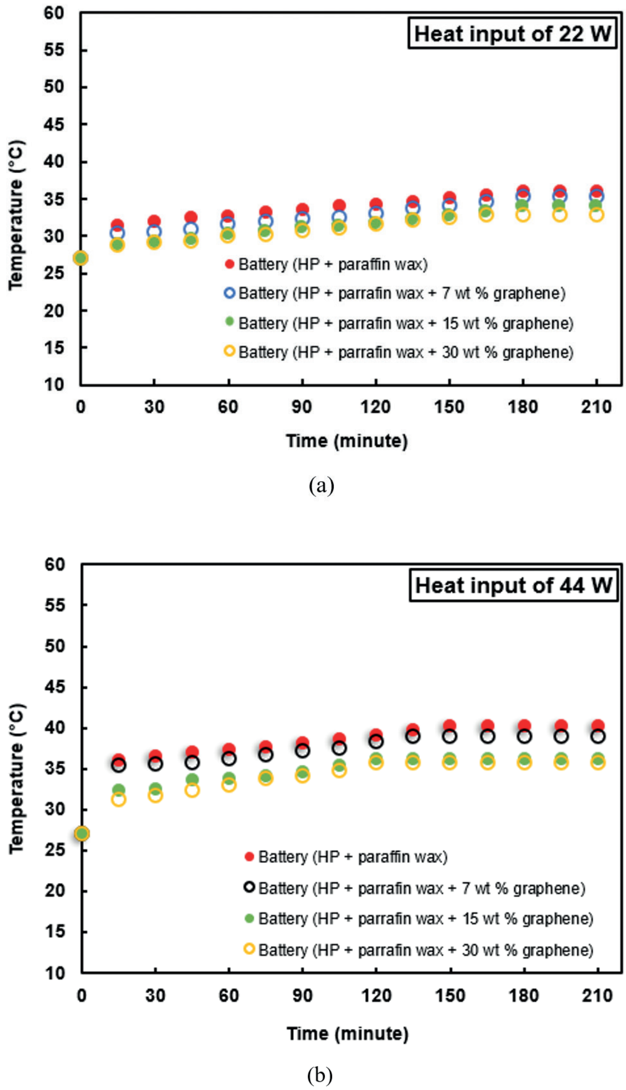
Fig. 4. Maximum temperature of battery, battery with heat pipe, and battery with heat pipe and PCM during experiments

The temperature different of battery only with battery with heat pipe are bigger at heat input of 44 W and 66 W than 22 W. As a result, the battery temperature decreases more significantly, as indicated by the larger temperature difference between the battery alone and the battery equipped with a heat pipe and phase change material (PCM). As shown in Figure 4, the temperature differences for heat loads of 44 W and 66 W are 21.69°C and 36.66°C, respectively, which are notably higher than the temperature difference at a heat load of 22 W, which is 9.1°C.

https://doi.org/10.14669/AM/215079

3.2. Cooling Performance of heat pipe with graphene- enhanced PCM for EV batteries

Figure 5 illustrates the effect of graphene addition to paraffin wax on the thermal management performance of a battery using a combined heat pipe and PCM cooling system.



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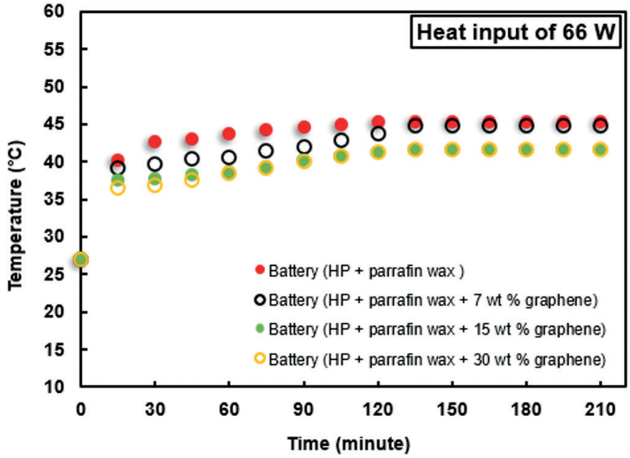

(c)

Fig. 5. Effect of graphene addition into PCM on the temperature of a battery using a combined heat pipe and PCM cooling system at different heat load (a) 22 W, (b) 44 W, (c) 66 W

Three distinct heat input levels 22 W, 44 W, and 66 W were applied to battery modules integrated with HP + PCM systems containing 0%, 7%, 15%, and 30% (m/m) graphene. Across all heat loads, the system with unmodified paraffin wax exhibited the highest operating temperatures. In contrast, batteries cooled with graphene-enhanced PCM showed a consistent reduction in temperature, with greater graphene content leading to more significant thermal regulation improvements. At the lowest heat input of 22 W, the maximum battery temperature with pure paraffin wax stabilized at approximately 35°C, while the addition of 30% (m/m) graphene reduced this value to around 31°C. This trend was further emphasized under higher heat loads.

With a heat input of 44 W, the temperature difference between the unmodified and the 30% (m/m) graphene PCM system increased to approximately 4°C. At the highest heat input of 66 W, the benefit of graphene addition was most pronounced. The battery with HP and pure paraffin reached nearly 50°C, while the system with 30% (m/m) graphene maintained a temperature closer to 41°C, representing a substantial improvement in thermal mitigation. Interestingly, at 66 W heat input, the battery system using 30% (m/m) graphene in paraffin sometimes shows slightly higher temperatures than the one using 15% (m/m) graphene, especially at later stages of the experiment. This trend doesn't follow the expected pattern seen at lower heat inputs, where more graphene always led to lower temperatures.

Figure 6 illustrates the peak operating temperatures of a battery under various cooling configurations at three different heat loads. The configurations include battery only, a heat pipe (HP) system, and combinations of HP with paraffin wax-based phase change materials (PCMs), both with and without graphene additives at varying concentrations (7, 15, and 30% m/m).

As expected, the battery without any cooling system (blue bars) exhibited the highest temperatures across all heat load conditions, reaching 50.2°C, 70.3°C, and 89.0°C at 22 W, 44 W, and 66 W respectively. The addition of a heat pipe alone provided a notable reduction in temperature, with peak values decreasing to 38.4°C, 43.5°C, and 49.5°C, demonstrating the heat pipe's effectiveness in enhancing convective and conductive heat dissipation.

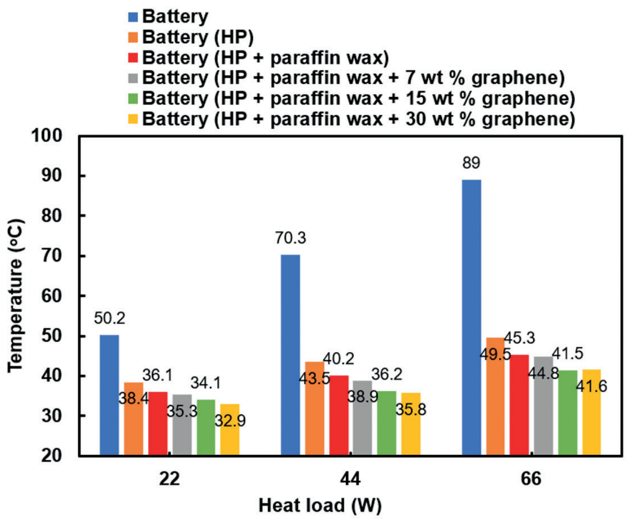

Fig. 6. Maximum battery temperature profiles under different cooling systems at varying heat loads.

4. Discussion

4.1 Discussion on Cooling performance of heat pipe and heat pipe–PCM system for EV batteries

The heat input from the heater elevated the battery surface temperature. Due to the superior thermal conductivity of the heat pipe, the generated thermal energy was rapidly extracted from the battery surface and dissipated into the ambient air. The paraffin wax as phase change material was inserted to enhance the heat transfer. The paraffin wax used in this study are effective to decrease temparature of battery as it has melting temperature of 50°C which is at the range of temperature safe of battery.

https://doi.org/10.14669/AM/215079

The substantial reduction of battery temperature using heat pipe and PCM highlights the effectiveness of heat pipe and heat pipe with PCM in enhancing the heat dissipation process. The increased heat transfer rate facilitated by the heat pipes lowers the internal energy accumulation within the battery simulator, thus maintaining a lower operating temperature. In the next set of experiments, the heat rejection was enhanced by adding a layer of paraffin wax around heat pipe, aiming to further reduce the battery temperature. Paraffin wax, a type of phase change Material (PCM), has a melting point of 50°C, which existed at the recommended operating temperature range of most batteries (typically up to 60°C). This means that under normal battery operation, the paraffin wax is in its solid state and also begins to melt into liquid. Therefore, it plays a role in cooling due to its ability to absorb sensible heat and also latent heat during phase change.

Despite its low thermal conductivity, paraffin wax significantly improved the cooling performance when combined with the heat pipe. This is because it can absorb and store a large amount of heat, thereby reducing the thermal load on the battery. The improved performance is primarily due to the paraffin wax's latent heat storage, rather than sensible heat. Since the operating temperatures of the battery at heat loads of 44 W and 66 W exceed the paraffin wax's melting point (reaching 59.69°C and 79.96°C respectively), the phase change that occurs allows the wax to absorb latent heat.

Interestingly in Figure 4, higher heating powers resulted in relatively lower battery simulator temperatures when heat pipes were employed. This is attributed to the heat pipes' ability to transfer more thermal energy to the ambient environment at elevated temperatures. However, the rate of heat transfer increase was not directly proportional to the increase in heating power. The thermal resistance of the heat pipe decreased with increasing heat load, measured at 0.38 K/W, 0.18 K/W, and 0.14 K/W for 22 W, 44 W, and 66 W, respectively. This behavior is consistent with the findings reported by Putra et al [19], indicating improved thermal performance of heat pipes under higher thermal loads.

4.2. Discussion on Cooling Performance of heat pipe with graphene-enhanced PCM for Ev batteries

Paraffin wax, although excellent in storing latent heat, suffers from low thermal conductivity (typically around 0.2 W/m·K). This limitation can cause uneven melting and slower heat absorption rates, leading to localized overheating in battery systems. To further improve the thermal performance of the PCM in the battery cooling system, incorporating graphene into the PCM can significantly enhance its thermal conductivity. Graphene, known for its exceptional heat conduction properties, facilitates faster heat transfer within the PCM, allowing the latent heat storage process to occur more efficiently and uniformly. By dispersing graphene nanoparticles throughout the PCM matrix, hotspots

https://doi.org/10.14669/AM/215079

can be minimized, and the phase change can be more fully utilized across the entire volume of the material.

The trends as shown in Figure 5, may be attributed to the fact that increasing the amount of solid filler (graphene) reduces the volume fraction of the actual PCM, thereby decreasing the amount of energy that can be stored as latent heat. At high graphene content, like 30% (m/m), the PCM may melt faster and lose its thermal buffering capacity earlier, causing the temperature to rise faster after that point. In addition, at higher concentrations, it becomes increasingly difficult to maintain a uniform dispersion of graphene within the paraffin. Poor dispersion can lead to thermal bottlenecks or localized areas with lower thermal conductivity, which in turn reduces the overall effectiveness of the composite. These inconsistencies may only become significant under higher heat flux conditions, such as at 66 W.

The incorporation of paraffin wax as a PCM in conjunction with the heat pipe (as shown in Figure 6) further improved thermal regulation, with maximum temperatures reduced to 36.1°C at 22 W, 40.2 °C at 44 W, and 45.3°C at 66 W. This improvement is attributed to the latent heat absorption capability of the PCM during phase transition. However, the most significant enhancement in thermal management was observed with the addition of graphene to the PCM. The system using HP and paraffin with 30% (m/m) graphene consistently exhibited the lowest temperatures: 32.9°C, 35.8°C, and 41.6°C at 22 W, 44 W, and 66 W respectively.

Notably, the composite with 15% (m/m) graphene also performed nearly as well, particularly at the highest heat load, where its peak temperature (41.5°C) was nearly identical to that of the 30% (m/m) configuration (41.6°C). This finding suggests a potential saturation point beyond which additional graphene contributes marginal improvement due to factors such as reduced PCM content and dispersion limitations. At lower heat loads, however, higher graphene content yielded more noticeable thermal benefits.

Overall, the results demonstrate that combining a heat pipe with a graphene-enhanced PCM significantly improves the cooling performance of battery systems, especially under high thermal stress. These systems effectively limit temperature rise, enhancing battery safety and operational stability, and are promising solutions for thermal management in electric vehicles and other high-power applications.

5. Conclusions

This study systematically investigated the thermal performance of various battery cooling systems, focusing on the integration of heat pipes (HP) and phase change materials (PCMs) enhanced with different weight percentages of graphene. Through experimental analysis at

https://doi.org/10.14669/AM/215079

multiple heat loads (22 W, 44 W, and 66 W), the effectiveness of each configuration in maintaining safe and stable battery temperatures was evaluated.

The results clearly demonstrate that the combination of HP and PCM significantly improves thermal management compared to passive cooling or HP alone. Furthermore, the incorporation of graphene into the PCM matrix notably enhances the composite's thermal conductivity, resulting in lower peak battery temperatures across all tested heat loads. The system containing 30% (m/m) graphene consistently achieved the best cooling performance, with the lowest temperature recorded at each heat input level. However, at the highest heat load (66 W), the temperature difference between the 15% and 30% (m/m) graphene-enhanced systems became marginal, suggesting a possible saturation point in thermal performance gains. This behavior may be attributed to reduced PCM volume and dispersion challenges at higher graphene concentrations.

Overall, the findings underscore the potential of graphene-enhanced PCMs in advanced thermal management systems for electric vehicle batteries. Such hybrid systems can effectively delay thermal runaway, enhance battery lifespan, and improve operational safety, especially under high power demands. From an industrial perspective, the HP+PCM+graphene configuration shows strong promise in meeting the stringent requirements of current EV battery thermal management standards, particularly the need to maintain cell temperatures below 60°C with minimal temperature gradients across modules. Nonetheless, practical deployment will require further optimization to ensure scalability, cost-effectiveness, and durability under real-world drive cycles. Future work may therefore focus on improving graphene dispersion techniques, validating system performance with real battery packs under dynamic operating conditions, and assessing compliance with automotive safety and performance regulations.

6. Acknowledgement

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7. Nomenclature

EV	Electric Vehicle
PCM	Phase Change Material
BTMS	Battery Thermal management System
HP	Heat Pipe

8. References

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