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Comparative Evaluation of PCM, Air Cooling, and Hybrid PCM-Air Cooling for Thermal Management of a Dry 18650 Cell

Armaan Mittal
mittalarmaan5@gmail.com

ABSTRACT

Thermal management is crucial to the safe, reliable performance of lithium-ion batteries. The thermal performance of a dry 18650 cell is experimentally compared in four states: no cooling, phase change material (PCM) cooling, fan cooling and hybrid PCM + fan cooling. The temperature of the cells was recorded during the 20 min experimental period, and the thermal responses of the four configurations were compared. The no-cooling condition achieved a temperature of 28.40 °C at 20 min, while the PCM, fan and hybrid PCM + fan cooling conditions had temperatures of 27.48, 26.10 and 25.38 °C, respectively. The corresponding final-temperature differences from the no-cooling condition were 0.92, 2.30, and 3.02 °C. Under the experimental conditions tested, the PCM + fan configuration produced the lowest recorded battery temperature compared with PCM cooling, fan cooling, and no cooling. Recorded cell temperatures remained below 30 °C, below the approximately 43 °C PCM melting point; latent-heat storage was not demonstrated. Unequal first-recorded temperatures and current profiles, together with undocumented ambient temperatures and replication, limit causal attribution to cooling alone. The robustness and applicability of the hybrid system should be further investigated under various discharge rates, ambient temperatures, airflow conditions and longer operating durations.

Keywords: *Lithium-ion battery, 18650 cell, battery thermal management, phase change material (PCM), air cooling, hybrid cooling, thermal performance*

1. INTRODUCTION

The high energy density of lithium-ion batteries compared to other electrical energy-storage technologies makes them popular in portable consumer electronics such as mobile phones and laptops (Alternative Fuels Data Center: Batteries for Electric Vehicles, n.d.). They have grown significantly into the electric vehicle and stationary energy storage market, with over 190 GWh of battery energy storage deployed globally through 2023, more than 80% of which was lithium-ion batteries. In 2025, the global lithium-ion battery market also surpassed USD 150 billion and is expected to grow further (International Energy Agency, 2026).

Even with this rapid growth, thermal management is still a major challenge during the operation of the battery. Electrochemical and parasitic reactions can be accelerated by heat generation, which may result in additional heat buildup and, in extreme cases, thermal runaway and fire. High temperatures can also cause capacity degradation and decrease the efficiency and service life of the battery. It is therefore crucial to keep the cell within an operating temperature range for safe and reliable operation (Ma et al., 2018).

There are a number of battery thermal management systems (BTMS) that have been developed to solve this problem. Air cooling is a relatively simple, light and low-cost way of cooling but can be insufficient in high thermal loads. The heat transfer is typically higher, but the system is more complex and could be subject to leakage issues with liquid cooling. The heat-pipe system has a high heat transfer capacity and can enhance the uniformity of temperature, but it is difficult to integrate it into the whole battery pack (Wen et al., 2025b). Phase change materials (PCMs) offer passive thermal control by absorbing heat when they change phase and can decrease the requirement for constant active cooling but have a relatively low thermal conductivity which may restrict heat transfer rates. Hence, the combination of PCM systems with active cooling techniques is being increasingly explored (Schaefer-Brown & YPFS, Yale School of Management, 2025; Wen et al., 2025b).

It has been reported that thermal performance is better when PCM is combined with other cooling methods. Incorporation of PCM with other thermal management methods can enhance the thermal performance and decrease the cooling power demand, as reported by Akkuş and Işık (2025). Likewise, Rahmani et al. (2024) have pointed to the potential of hybrid PCM systems with air or liquid cooling for thermal load management, especially at high discharge rates. The results indicate that the passive PCM cooling system could be used as an active cooling system, as it can offer a compromise between heat absorption, heat dissipation, system complexity and energy consumption.

But, comparatively, fewer experimental studies have directly compared no cooling, PCM cooling, air cooling and hybrid PCM–air cooling under similar experimental conditions, especially monitoring thermal and electrical responses simultaneously. Hence, a low-complexity, comparative experimental study of these four thermal-management configurations with documented operating conditions is required to determine their relative effectiveness.

For this purpose, this study experimentally tests the thermal and electrical performance of a dry 18650 cell under four different thermal-management conditions: no cooling (control), PCM cooling, air cooling, and hybrid PCM–air cooling. Under load, the temperature, voltage and current of each cell are measured and compared to assess the performance of the four configurations and the effectiveness of the hybrid cooling compared to the individual cooling strategies.

2. MATERIALS AND METHODS

2.1 Study Design

This experimental study compared passive Phase Change Material (PCM) cooling, active air cooling and a hybrid PCM-air cooling system for thermal management of a dry 18650 cell during discharge. Four configurations were studied using the same nominal electrical load. Battery surface temperature, voltage, current and power were monitored for 20 min. The first-recorded temperatures and current profiles differed between configurations, so cooling was not the only factor that could influence the measured temperatures.

2.2 Materials

The test battery was a commercially available 3.7 V, 2500 mAh rechargeable dry 18650 cell (Consonantiam). Passive thermal management was realized by using OP43 Phase Change Material (BP Refcool), which is a paraffin wax-based PCM with a phase transition temperature of about 43°C. This describes the material's phase-change capability; the present tests did not demonstrate melting because recorded cell temperatures remained below 30 °C.

The microcontroller platform for data acquisition was an Arduino Uno R3 microcontroller and was used with the sensing modules throughout the study. The surface temperature of the battery was measured with a waterproof DS18B20 digital temperature sensor, which was firmly placed on the outside of the battery to ensure continuous monitoring of the battery's surface temperature. An INA219 current sensing module was used to measure electrical parameters such as voltage, current and instantaneous power.

Active air cooling was achieved by a 12 V brushless DC fan, and another 12V DC fan was used as the nominal discharge load; it was not a regulated constant-current load. The circuits were built using standard electrical connectors, connecting wires, soldering materials and assembly accessories. Safety precautions were observed in the laboratory, such as wearing protective gloves and safety eyewear during all experimental procedures.

2.3 Phase Change Material

The passive thermal management medium was a commercially available Phase Change Material (OP43, BP Refcool) based on paraffin wax, with a melting temperature of approximately 43 °C. In general, PCM stores latent heat during melting and releases it during solidification. In these tests, however, recorded cell temperatures remained below 30 °C and the PCM phase state was not directly measured. Melting, latent-heat absorption and latent-heat saturation therefore cannot be claimed. Any heat storage below the melting point would be sensible heat storage; its contribution was not separately quantified.

2.4 Experimental Setup

The experimental setup was designed to test the thermal performance of a single cylindrical 18650 lithium-ion battery using the same nominal electrical load and continuously monitor both thermal and electrical parameters. The experimental setup consisted of an 18650 battery with a 12 V DC fan as the electrical load. The surface temperature of the battery was measured continuously with the help of the DS18B20 digital temperature sensor placed in direct contact with the battery surface, and the voltage, current and instantaneous power were measured by using the INA219 current sensing module, which was interfaced with the Arduino Uno microcontroller. For the air-cooling and hybrid cooling conditions, a second 12 V DC fan was positioned next to the battery to provide active cooling.

In passive thermal management experiments, the battery was covered on four sides with OP43 PCM, with the electrical terminals left uncovered for safe electrical connections. With active cooling, a 12 V brushless DC fan was placed next to the battery to ensure continuous forced air flow during discharge. The same instrumentation, electrical load, sensor location were used for all experiments. Equivalent ambient conditions, initial thermal states and electrical power were not established by the supplied records. The cooling fan power source is not documented, so it cannot be confirmed whether it used an external supply or drew power from the test cell.

2.5 Experimental Conditions

Four experimental setups were explored to examine the performance of various thermal management strategies.

- **Condition I:** In the control configuration, no active or passive cooling technique was used, and the 18650 lithium-ion battery was directly connected to the 12V DC fan load. The heat produced in the battery during discharge was released naturally by convection to the ambient air. This configuration was chosen as a reference and compared to the various cooling strategies explored in the study.

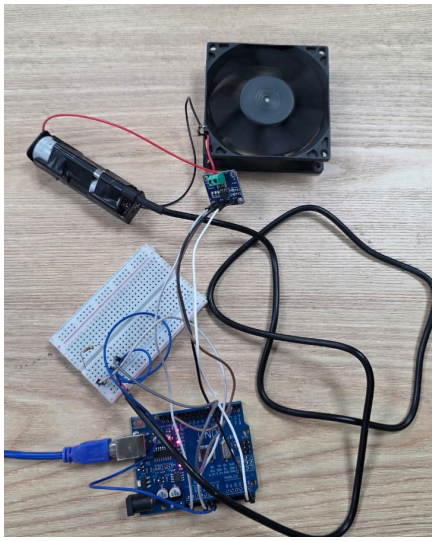


Figure 1: Load was connected without any cooling system.

- **Condition II (**Passive PCM Cooling): For passive cooling, four sides of the battery were covered with OP43 phase change material. The PCM was in direct contact with the battery surface so that conductive heat transfer between the battery and the PCM could take place. Recorded cell temperatures were below the PCM melting point, so any PCM heat absorption would be through sensible heating rather than demonstrated latent heat storage. During this experiment no active airflow was used.

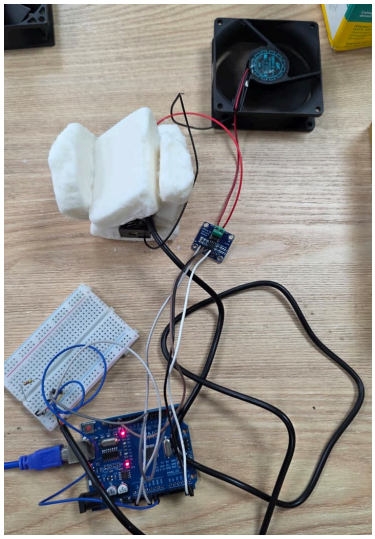


Figure 2: OP43 Phase Change Material passively absorbed heat from the battery surface

- **Condition III (**Active Air Cooling): The active cooling configuration was to have a second 12 V brushless DC fan blow air through the battery during discharge. The electrical load was the first 12 V brushless fan and the second fan was placed beside the battery to perform active cooling.

The battery produced heat and the heat was transferred away by forced convection, leading to higher heat transfer rates than natural convection. This experimental condition was performed without the use of a PCM.

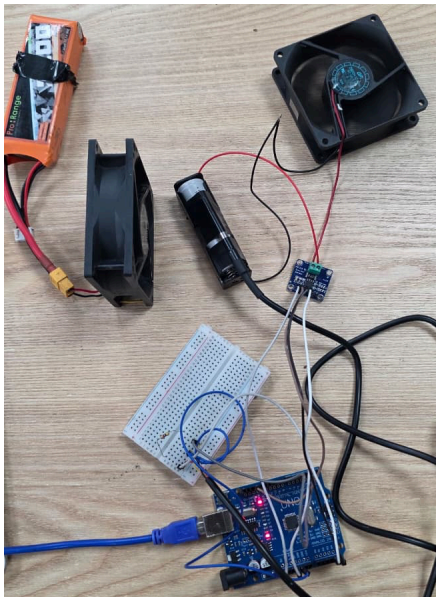


Figure 3: 12V Fan actively cooled the dry 18650 cell

- **Condition IV: (**Hybrid PCM-Air Cooling): The cooling system was a hybrid system with both passive and active thermal management. The 12 V brushless DC fan was used to cool the battery, which was sandwiched between OP43 PCM on four sides, and was kept on all the time. The first 12 V brushless DC fan was used as the electrical load. In this setup, the PCM could provide sensible heat storage while forced air could enhance heat transfer from the battery surface and PCM. Latent heat storage was not demonstrated at the recorded temperatures.

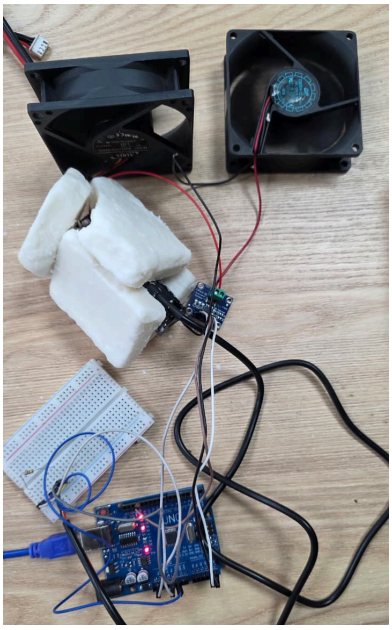


Figure 4: 12V Fan actively cooled the dry 18650 cell and OP43 Phase Change Material passively absorbed heat from the cell surface

2.6 Experimental Procedure

An 18650 lithium-ion battery was inserted into the experimental set-up for each experimental condition under the cooling strategy under investigation. The INA219 monitoring module was used to connect the battery to the 12 V DC fan used as the electrical load, while the DS18B20 temperature sensor was firmly mounted on the surface of the battery. Under the active air-cooling and hybrid cooling conditions, a second 12 V DC fan was placed beside the battery and was always on to cool the battery. The experiment was conducted and the Arduino Uno microcontroller was used to record the temperature, voltage, current and power readings throughout the experiment.

The electrical load was connected and data collection started immediately after connection, continuing for 20 minutes at regular measurement intervals. The same nominal load, instrumentation and sensor placement were utilized. But there is no separate documentation of ambient temperature for no cooling, PCM, fan or PCM + fan. Also, no information is provided on whether the same physical cell was reused, on the recharge/state of charge history of the cell, or on whether the cell was allowed to reach a common starting temperature. The first readings are not at time zero but at 1 min and vary from test to test. The data set consists of one time series reported for each condition, with the number of experimental repetitions not specified in the data records. Therefore, independent replication, repeatability and statistical significance are not possible; the reported traces should be considered as descriptive observations and not as replicated estimates.

2.7 Performance Evaluation Strategy

The temperature and electrical profiles were compared descriptively for the four configurations over the 20-min period recorded. The final temperatures and changes from the first temperature reading were assessed. These records do not guarantee the full discharge cycle performance or battery life. The comparison does not isolate the effect of cooling at an equal thermal or electrical load due to the difference in initial temperatures and measured currents. Independent repeat measurements are not recorded and therefore no error bars or inferential statistics reported.

3. RESULTS

3.1 Comparative Thermal Performance

The dry 18650 cell was tested for the four experimental conditions: no cooling (control), PCM cooling, fan cooling, and hybrid PCM + fan cooling. The effectiveness of the various thermal management strategies were compared by measuring the temperature over a 20 min experimental period.

In the early stages of the experiment the same temperature profile was seen in all four conditions. The temperature recorded during the first 5 min was lower and then gradually rose for the rest of the experiment. Although this was the general starting trend, there were definite differences in the absolute temperatures achieved for each cooling condition.
The no-cooling condition always had the highest temperatures. The temperature dropped from 27.06 °C at 1 min to 26.37 °C at 5 min and then slowly rose to 28.40 °C at 20 min, while the PCM cooling trace reached a minimum of 26.06 °C at 5 min and increased to 27.48 °C at 20 min.

The fan cooling trace was lower than the PCM cooling trace. During the experiment the temperature was kept at 25.25 °C to 26.10 °C. The hybrid PCM + fan configuration recorded the lowest temperatures among the four conditions tested. The minimum temperature was 24.75 °C at 5 min and slowly rose to 25.38 °C at 20 min.

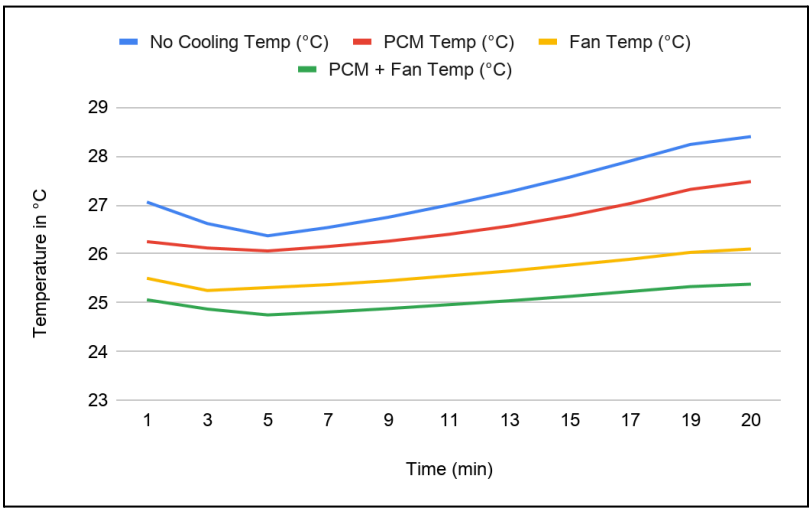


Figure 5. Temperature variation of the dry 18650 cell under different cooling conditions.

Time (min)	No Cooling (°C)	PCM (°C)	Fan (°C)	PCM + Fan (°C)
1	27.06	26.25	25.5	25.06
3	26.62	26.12	25.25	24.87
5	26.37	26.06	25.31	24.75
7	26.54	26.15	25.37	24.81
9	26.75	26.26	25.45	24.88
11	27.0	26.4	25.55	24.96
13	27.27	26.57	25.65	25.04
15	27.57	26.78	25.77	25.13
17	27.9	27.03	25.89	25.23
19	28.24	27.32	26.03	25.33
20	28.4	27.48	26.1	25.38

Table 1. Temperature profile of the mini Li-ion battery pack under the four cooling conditions.

At 20 min, the final temperatures were 28.40 °C for no cooling, 27.48 °C for PCM cooling, 26.10 °C for fan cooling, and 25.38 °C for PCM + fan cooling. Relative to the no-cooling control, the final temperature was therefore 0.92 °C lower with PCM cooling, 2.30 °C lower with fan cooling, and 3.02 °C lower with the hybrid PCM + fan configuration. These are unadjusted endpoint differences, not isolated cooling effects. The first-recorded temperatures at 1 min were 27.06, 26.25, 25.50 and 25.06 °C, respectively: the no-cooling and hybrid traces already differed by 2.00 °C. Temperature changes from 1 to 20 min were

+1.34, +1.23, +0.60 and +0.32 °C, respectively. This baseline comparison does not correct for unknown ambient conditions or unequal heat generation, and time-zero temperatures were not available.

Cooling condition	Minimum temperature (°C)	Temperature at 20 min (°C)	Temperature Reduction vs. no cooling at 20 min (°C)
No cooling	26.37	28.4	—
PCM	26.06	27.48	0.92
Fan	25.25	26.1	2.3
PCM + Fan	24.75	25.38	3.02

Table 2. Summary of thermal performance at the end of the 20-min test.

***Note:** Final-temperature differences are calculated relative to the no-cooling temperature at 20 min (28.40°C) and are not adjusted for unequal initial temperatures or currents.

3.2 Electrical Current Response

Temporal patterns were different for the four experimental configurations, as revealed by current measurements. Under the current under no-cooling condition, the current gradually reduced from 10.5 mA at 1 min to 8.38 mA at 20 min. In the PCM-only condition, the current increased from 6.4 mA to a maximum of 11.2 mA at 5 min and then decreased slowly to 10.45 mA at 20 min.

With fan cooling, the current was 10.3 mA at 3 min and dropped to 7.60 mA at the end of the experiment. For the hybrid PCM + fan configuration, the current drop was the greatest, from 13.5 mA at 1 min to 7.2 mA at 5 min, after which the current gradually decreased but remained fairly stable at 6.90 mA at 20 min. These different current profiles were kept as ancillary electrical measurements, and temperature was used as the main descriptive response. The currents were not the same when the same fan load was used: a motor load is not a constant current load. The differences in cell state of charge, supply voltage, motor operating state, wiring resistance or measurement setup might be contributing, but it is not possible to determine from the supplied records. There is also no documentation on the cooling fan supply and measurement boundary. The unequal electrical loading may alter the heat generation and may lead to a distortion in the thermal comparison, and the current differences may not be due to cooling alone.

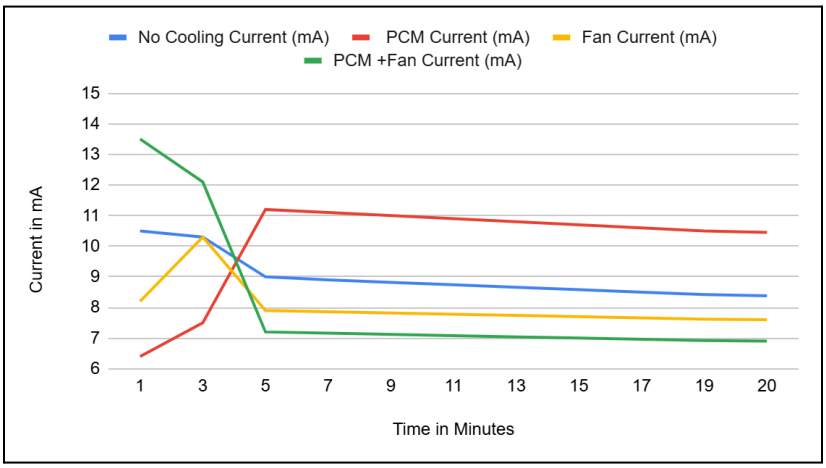


Figure 6. Current variation of the dry 18650 cell under different cooling conditions.

Time (min)	No Cooling (mA)	PCM (mA)	Fan (mA)	PCM + Fan (mA)
1	10.5	6.4	8.2	13.5
3	10.3	7.5	10.3	12.1
5	9.0	11.2	7.9	7.2
7	8.9	11.1	7.86	7.16
9	8.82	11.0	7.82	7.12
11	8.74	10.9	7.78	7.08
13	8.66	10.8	7.74	7.04
15	8.58	10.7	7.7	7.0
17	8.5	10.6	7.66	6.96
19	8.42	10.5	7.62	6.92
20	8.38	10.45	7.6	6.9

Table 3. Current measurements under the four experimental conditions.

3.3 Voltage Response

The reported voltage was about 1.0 V in all four conditions, between about 0.997 and 1.017 V. These readings are not confirmed cell terminal voltages, nor nominal cell voltage. The INA219 measurement channel, wiring, ground reference, code conversion and units require checking against the original logs and an independent multimeter measurement at the cell terminals. A nominal rating is not a correction factor, and the reported readings are not corrected to assumed 3.7 V readings. Until the discrepancy is resolved, voltage-based power, discharge state and equal-power loading cannot be reliably determined.

There is no voltage graph available. The unconfirmed voltage readings are kept as a voltage measurement limitation and not as a sign of similar electrical functioning.

3.4 Overall Comparative Performance

The hybrid PCM + fan configuration had the lowest temperatures in the 20 min tests, followed by fan cooling, PCM cooling and no cooling. This ordering refers to the traces as observed; differences in initial temperatures, current profiles and undocumented ambient conditions make it difficult to conclude that the differences are solely due to the cooling method.

The electrical measurements are the descriptive outcomes that are identified as limitations of comparability between tests, and temperature is the main descriptive outcome. The battery operating states defined by the un-verified voltage readings are not comparable. Therefore, the ranking of the cooling effectiveness observed in these tests is not a general ranking.

4. DISCUSSION

The hybrid PCM + fan configuration produced the lowest recorded battery temperature, followed by fan cooling, PCM cooling and no cooling. The endpoint values and their differences are reported in Section 3.1 and Tables 1–2. Because the traces began at different recorded temperatures and had different currents, these observations do not by themselves demonstrate a causal advantage of hybrid cooling.

Sensible heat storage in the PCM and forced convection are possible contributors to the lower hybrid trace, but their individual contributions were not measured. The present temperatures do not support a latent-heat mechanism. Published investigations examine hybrid cooling under other operating conditions. Ranjan et al. (2024) reported improved thermal regulation of cylindrical lithium-ion cells using PCM-assisted air cooling, while Zhou et al. (2024) demonstrated that a hybrid system combining internal PCM with external air-jet cooling provided superior thermal performance compared with individual cooling approaches. Although their systems involved different operating conditions and more advanced thermal-management configurations, those results do not verify the mechanism or causal cooling advantage in the present tests.

An important result of the present study is that the fan cooling trace was lower than the PCM cooling trace. This finding should be interpreted as being specific to the experimental conditions rather than as evidence that air cooling is universally more effective than PCM. The relative performance of PCM and air cooling is strongly dependent on heat-generation rate, airflow conditions, convective heat-transfer coefficient, PCM melting characteristics, and operating duration. Afrand et al. (2025) specifically investigated the relative effectiveness of PCM and air cooling and demonstrated that the advantage of PCM changes with C-rate and convective heat-transfer conditions. Their results indicate that PCM can outperform air under certain operating conditions, whereas increased convective heat transfer can improve the effectiveness of air cooling. Therefore, the fan > PCM relationship observed in the present experiment is a condition-dependent finding.

The changes from the first available readings, reported in Section 3.1, provide a baseline comparison alongside the absolute temperatures. A smaller observed rise in the hybrid trace is compatible with lower heat accumulation, but cannot distinguish cooling effects from unequal electrical loading or ambient conditions. The early temperature decrease also means that the 1-min readings cannot be assumed to represent an equilibrated starting state.

The gradual temperature rise in the PCM-only trace cannot be interpreted as latent-heat saturation. Recorded cell temperatures remained below 30 °C, well below the approximately 43 °C melting point, and no PCM phase-state measurements were reported. Sensible heating and heat exchange with the surroundings are possible, but were not quantified separately. Published limitations of standalone PCM systems (Afrand et al., 2025; Sajedi & Molaeimanesh, 2024) therefore provide context rather than evidence that melting or saturation occurred in this experiment.

The present results are also broadly comparable with recent experimental studies of hybrid battery thermal-management systems. Sajedi and Molaeimanesh (2024) investigated a hybrid PCM and refrigerated-air system with extended surfaces and reported improved thermal regulation compared with individual cooling mechanisms. Zhou et al. (2024) also showed that the maximum temperature and temperature uniformity can be enhanced by using air-jet cooling along with PCM compared to using either method alone. These studies involved more complex systems such as controlled airflow, extended surfaces and optimized thermal configuration. Hence, it is not possible to compare their absolute temperature drops directly with those of the present experiment. The present lower hybrid trace is qualitatively compatible with those reports, but experimental confounding prevents establishing the same benefit here.

The present study is unique compared to numerous published battery thermal-management studies in that the experimental design was kept deliberately simple. Controlled C-rate, high ambient temperature, PCM formulations with engineered or nano-enhanced PCM, fins, heat pipes, or precisely controlled airflow conditions have been used in previous studies (Ranjan et al., 2024; Zhou et al., 2024; Sajedi & Molaeimanesh, 2024). The advantage of this experiment is, however, the direct comparison of four conditions: no cooling, PCM, fan, and PCM + fan, over the same 20-min duration. The records do not confirm reuse of the same physical cell or equivalent initial state of charge. This offers a descriptive comparison whose thermal differences require confirmation under matched initial and electrical conditions.

The electrical measurements materially limit interpretation of the temperature comparison. Different current profiles mean that heat generation was not established as equal, and the approximately 1.0 V readings remain unverified. These limitations cannot be removed simply by treating temperature as the primary outcome. Repeat tests should verify cell-terminal voltage, log current and power, and document whether cooling-fan power is external or included in the cell load.

The hybrid configuration recorded the lowest temperatures under the conditions tested; a general claim that it is the best cooling method is not supported. Published hybrid systems provide a rationale for further testing (Ranjan et al., 2024; Zhou et al., 2024; Sajedi & Molaeimanesh, 2024), while Afrand et al. (2025) shows that relative PCM and air-cooling performance depends on operating conditions. The present experiment does not demonstrate latent-heat operation or isolate the cooling contribution.

A major drawback in the present study is the time of the experiment (20 min). This time is used to compare initial thermal response, but it does not provide any information on the long-term heat-storage performance of the PCM or the long-term performance of the hybrid system. Further testing is thus recommended to continue this operation for a longer duration and repeat the discharge cycles to test whether the lower hybrid temperature persists under matched initial temperatures, verified electrical loading and documented ambient conditions. The number of repetitions in the present work is not documented, so repeatability remains unestablished.

The second constraint was the experiment was only performed at one operating condition, without a controlled discharge-rate sweep or documented per-test ambient temperatures. Future work should investigate the four configurations under various C-rates and ambient temperatures, as the relative effectiveness of PCM and forced convection varies with the thermal load (Afrand et al., 2025). This would determine whether the observed temperature ordering persists with increased heat generation and adequate independent replication.

The fan airflow rate and the characteristics of the PCM were not also systematically varied. The convective heat transfer is directly influenced by the airflow rate, and the thermal-buffering capacity of the PCM is influenced by its mass, thickness, melting temperature, thermal conductivity, and latent heat. Future experiments should, therefore, independently change the fan speed and quantity/type of PCM to find the combination which gives the maximum temperature reduction with the least auxiliary energy requirement.

The other extension that is important is the assessment of cooling energy consumption. The cooling fan's power source and energy use were not documented, so its contribution to cell loading and total system energy consumption cannot be established. Future studies should determine fan power and report a thermal-performance metric that correlates temperature reduction with auxiliary energy use. This would give a more realistic measure of the practical efficiency of the hybrid system.

Lastly, the present study is mainly based on the evaluation of temperature at the measured location. Future work should include the use of several temperature sensors or infrared thermal imaging to measure the temperature distribution and thermal non-uniformity within the cell or battery assembly. This is especially significant due to the recent hybrid BTMS studies that have shown that minimizing temperature differences is a critical aspect of battery thermal management (Zhou et al., 2024).

Therefore, optimization should be the next step of this work, and not just to increase the cooling intensity. The thermal and energy performance of the hybrid system could be optimized for practical

battery-management applications by systematically varying the quantity of PCM, the melting range, the fan airflow, the C-rate of the batteries, the ambient temperature, the test duration, and the cooling power.

5. CONCLUSION

The configuration of hybrid PCM + fan had the lowest temperature among the four configurations under the tested condition. This observation does not prove that the temperature differences were due to the cooling method alone, as the initial temperatures were recorded in one year and the current temperatures were not recorded, and the temperature readings from the approximately 1.0 V were not replicated.

The recorded cell temperatures were below the melting temperature of the PCM, which is about 43 °C, and thus latent-heat cooling was not shown. Confirmation needs matched initial cell temperatures and states of charge, cell re-use and ambient conditions documented, verified electrical load and cooling-fan power source, and independent repeat testing. Further tests and other discharge rates are required before the results can be extrapolated to other operating conditions.

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