Dean&Francis
ISSN 2959-6157

How does a low-temperature environment affect the discharge capacity and internal resistance of lithium-ion batteries

Zhiyang Fan

Olive tree international academy,Hangzhou, Zhejiang
Postcode: 310051
Email: scott_fan1020@163.com

Abstract:
The study investigated the performance degradation of 18650 lithium-ion batteries under low-temperature environment. A Arduino-based testing system was used to conduct comparative discharge experiments at 25℃ and approximately -10℃. The system detected and collected the real-time current, voltage and temperature data, and the discharge capacity was calculated by current integration. The results of this study reveal that low-temperature environment will greatly increase internal resistance, lower the discharge plateau and reduce capacity of a lithium-ion battery. The root cause lies in higher electrolyte viscosity and slow lithium-ion migration. The article summarizes existing optimization methods, analyzes experimental limitations, and provides practical improvement strategies for batteries used in electric vehicles and portable electronics.

Keywords: lithium-ion battery; 18650 cell; low-temperature discharge; internal resistance; capacity fading; Arduino experimental platform

1. Introduction

Nowadays, the performance of lithium-ion batteries such as 18650 cylindrical cells, which is one of the widest used lithium-ion batteries, is critically dependent on operating temperature. Although these batteries always have high energy density and high reliability under standard conditions, their efficacy significantly deteriorates in low-temperature environments (Ji Ke, 2024). This degradation presents as reduced capacity, increased internal resistance, and slower charge or discharge rates. These effects pose substantial amounts of challenges for electronic devices and electric vehicles (EVs) in low-temperature environment (Delos Reyes, J.R.M., Parsons, R.V. and Hoemsen, R., 2016). So, it is very essential to solve this limitation to enhance the reliability and usability of lithium-ion battery-powered products in regions with low temperatures.

How does low temperature affect the discharge performance of 18650 lithium-ion batteries compared to room temperature conditions? In this dissertation I will mainly focus on comparing the performance of 18650 lithium-ion battery under low-temperature and room-temperature conditions. I will use Arduino and some sensors to help to detect the data of the battery during the discharge process, which will just directly show out the data detected on the screen so that I can record these data in the form. From the experiment, I can investigate the main reasons that decrease the performance of lithium-ion batteries under a low-temperature environment. Based on the analysis of experimental data and literature review, I will further explore and propose some feasible optimization schemes.

Many research has documented the adverse effects of low temperatures on lithium-ion batteries. The most typical one is that low-temperature will slow down ion transport. This will increase electrolyte viscosity and limitations of electrode materials. However, many studies are rather general or theoretical. The aim of this work is to provide quantifiable data through detailed empirical testing of 18650 batteries in actual low-temperature scenarios, so that it can provide direct references for thermal management and battery design improvements in practical applications.

The main objectives of this study are to accurately measure the data changes of 18650 lithium-ion batteries in low-temperature and normal-temperature environments by building an experimental platform with Arduino, and to quantify the performance differences between low-temperature and normal-temperature operations. To draw relevant tables and charts based on the experimental data and analyze the electrochemical and physical causes behind the performance decline at low temperatures, and to propose and preliminarily verify feasible optimization solutions, such as preheating technology, in order to mitigate the impact of low-temperature effects on consumer electronics and electric vehicle power systems.

The structure of this thesis is arranged as follows: Firstly, through reading literature and examining scientific videos, the working principle of lithium batteries, the problems that occur in lithium batteries at low temperatures, and the existing mitigation strategies are understood. Secondly, set up the experiment equipment and do some testing to make sure the equipment works well. Then do the research. Subsequently, the empirical data obtained from the comparative tests are presented in the results section, and the research findings are interpreted in the discussion section and linked to the physical mechanisms. Finally, the conclusion section summarizes the core findings, outlines the proposed optimization suggestions, and offers prospects for future research directions aimed at enhancing the low-temperature adaptability of batteries for modern electronic and mobile applications.

2. Methodology

2.1 SECONDARY RESEARCH

In order to ensure the smooth progress of this experiment, I conducted systematic secondary data collection. The retrieval platforms included IEEE, CNKI, and YouTube, among others. The data included: understanding the working principle of lithium batteries; gaining some knowledge about the Arduino experimental platform; and the performance issues of lithium batteries and related electronic devices in low-temperature environments.

2.2 PRIMARY RESEARCH

Aim: To investigate the performance of 18650 lithium batteries under different low-temperature conditions using the Arduino experimental platform, and then provide improvement suggestions for current electric vehicle batteries based on the performance data.

Instrument and material selection: 1. Arduino uno r3. 2. 18650 lithium batteries. 3. INA219 I2C Bidirectional Current/Power Monitoring Sensor Module. 4. 18650 lithium battery case. 5. 50W 5-ohm cement resistor. 6. 4.7k-ohm resistor. 7. DS18B20-Digital temperature sensor.

As for the experiment environment. A plastic bottle with salted iced is chosen because it can guarantee that the environmental temperature is constantly under zero degrees Celsius(about -10 degree in the initial stage). The battery will be packed in an oil paper bag so that it will be affected by the environmental temperature and also the melted ice water will not come into directly contact with the battery.

2.3 Experimental procedure

First, I need to set up our experimental platform. I connect the Arduino with temperature sensors and voltage and current sensors, and then connect the Arduino to the computer. On the computer, I edit the code to read the sensor data, and the sensors can display the data read in real time on the computer screen.

Second, the experiment will be divided into two groups. The first group will be done under the room temperature. And the second group will be done under zero degree Celsius. This experimental equipment can automatically output the time, battery voltage, current, power and temperature. From these two different environments, I can make a comparison about their data and find out the influence on lithium-battery under low temperature environment.

ISSN 2959-6157

2.4 Data and information needed

The table below is used to record the data needed in the experiment

Time(min)	Low temp(°C)	Low pd(V)	Low current(A)	Room temp(°C)	Room pd(V)	Room current(A)
0						
1						
5						
10						
30						
60						
90						
120						
180						
210						
225						

2.5 Matters needed attention

1. Keep the experiment equipment away from tinder, to prevent fire.
2. Ensure that before the experiment start, the battery has to be fully charged.
3. Constant environmental temperature in the experiment.
4. The oil-paper bag must not be leaky.
5. The probe needs to be in close contact with the battery.

2.6 Data treatments and analysis

The experiment will be performed under both room temperature and under zero degree Celsius. The table mentioned above will record the data in both environments. Then draw two curve graphs of the power versus time based on the data. (two different environment). Compare and analyses the curve graphs under different temperatures and make a conclusion. As for some data that cannot be directly detected by the sensor, such as the capacity of the lithium-ion battery, I choose to use a method called current integration method. This is a useful method that can calculate the capacity of the lithium-ion batteries based on the current detected. (Mohammadi, F., Forgez, C., Nguyen, T.A. and Friedrich, G., 2022)

3. Literature Review

3.1 Background and Challenges of Lithium Battery Applications at Low Temperatures

Nowadays, lithium-ion batteries have been widely applied in various fields, including electric vehicles, aerospace engineering, polar exploration missions, and military equipment. However, the problem of inadequate low-temperature performance has become increasingly prominent in recent years, which severely restricts their practical application scope. The academic community generally holds the view that the performance degradation of lithium batteries in extreme low-temperature environments—such as polar regions, high-altitude aviation, and high-latitude military applications—has become the core bottleneck that limits their all-weather and all-scenario use (Gu Yushun, Wang Peihong, 2014). Relevant research findings (Gupta, A. and Manthiram, A., 2020) could indicate that when environmental temperature drops below 0°C, the capacity and output power of lithium batteries may decrease significantly, and this degradation trend might become more apparent as temperature continues to drop. Moreover, the significant empirical evidence may suggest that extremely cold weather substantially reduces the inherent performance of the battery itself. Furthermore, cold conditions might indicate that electric vehicles are forced to activate air conditioning systems for interior heating. Thus, findings may show this further increases overall power consumption. However, results could affect vehicle efficiency in ways that compound the initial battery degradation. Relevant research results show that low temperatures not only create "internal troubles" by reducing the energy density of lithium batteries but also cause "external troubles" by increasing the energy consumption of the vehicle's thermal management system. This dual challenge has forced researchers to reconsider the design logic of wide-temperature-range lithium batteries and explore more effective solutions. The significant empirical evidence could indicate that addressing the low-temperature performance problem of lithium batteries represents a critical and extremely urgent task in the current research field. Moreover, the important findings from high-latitude regions such as Russia, where winter temperatures may drop below -30°C, suggest that the driving range of electric vehicles is significantly reduced (Jaguemont, J., Boulon, L. and Dubé, Y., 2016). Additionally, the key evidence may indicate that outdoor service time of electronic devices is also severely limited due to rapid battery power loss. Thus, results may show space exploration and polar research demand even stricter standards. Furthermore, findings could suggest performance requirements grow more stringent still. Given that the significant results demonstrate that lithium batteries used in these fields must maintain stable charge-discharge performance within a wide temperature window ranging from -40°C to 60°C, the important evidence may suggest that this represents a critical operational constraint. In light of the key findings, the study could indicate that deeply understanding the mechanisms of low-temperature performance degradation may prove essential. However, research may show optimization methods remain underdeveloped. Therefore, evidence could suggest expanded application still requires further study.

3.2 Study on the Performance of Lithium Batteries at Low Temperatures and the Failure Mechanisms of Lithium Batteries at Low Temperatures

Low-Temperature Performance of lithium-ion batteries refers to the comprehensive performance indicators including capacity retention rate, rate capability, and cycle stability when the batteries operate under temperatures below 0°C. The research conducted by Ji Ke (2024) shows that lithium batteries lose the most energy and capacity when the ambient temperature drops below -10°C, and the performance degradation rate accelerates significantly with further temperature reduction. Through comparative analysis of the electrochemical behavior of lithium batteries under different temperature gradients, this study further confirmed that the optimal operating temperature window for lithium batteries is between 0°C and 40°C. Once the operating temperature breaches this critical range, various kinetic parameters of the battery will show obvious performance degradation, which directly affects the service life and reliability of the battery.

In the specific experiment carried out by Ji Ke (2024), several identical lithium batteries were divided into multiple groups, with 3–5 parallel samples in each group to ensure the reliability and repeatability of the experimental data. The batteries in each group were separately placed into temperature chambers set at different temperature points, including -40 ℃, -20 ℃, 0 ℃, 25 ℃, 40 ℃, and 60 ℃. The batteries were kept at each set temperature for 6–24 hours to ensure that they could fully cool down or heat through, reaching a stable thermal equilibrium state. After that, charge-discharge cycle tests were carried out on the batteries according to the standard test procedures, and key performance indicators such as discharge capacity retention rate, median voltage, internal resistance, and energy density were recorded in real time during the test process. The experimental data obtained were then used to draw corresponding curve graphs, and systematic data analysis was conducted to explore the relationship between temperature and battery performance. This experiment further verified that the optimal working temperature range of lithium-ion batteries is between 0°C and 40°C, which is consistent with the conclusions of most existing studies.

When discussing the specific low-temperature failure mechanisms of lithium batteries, past studies often analyzed them from the following two key factors (Luo, H., Wang, Y., Feng, Y.-H., Fan, X.-Y., Han, X. and Wang, P.-F., 2022), both of which are closely related to the inhibition of ion transport in the battery system. The first factor is that the viscosity of the electrolyte will increase significantly as the temperature decreases. This increase in viscosity will directly slow down the migration rate of lithium ions in the electrolyte and significantly reduce the ionic conductivity of the electrolyte. When the temperature drops below -30°C, some conventional electrolytes may even freeze, which will completely interrupt the ion conduction pathways in the battery and lead to the failure of the battery to work normally. The second factor is that the rate of lithium-ion intercalation into the anode material will decrease sharply during low-temperature charging. For example, when lithium-ion batteries are charged at normal temperature, the process of lithium ions being embedded into the anode is efficient and smooth, similar to the process of a sponge absorbing water; while in a low-temperature environment, this intercalation process will become extremely slow, just like frozen oil flowing slowly. The lithium ions released from the cathode material will take a long time to migrate and intercalate into the anode. Since the same charging current is used during the charging process, the lithium ions that cannot be intercalated into the anode in time will "queue up" and accumulate near the anode. The lithium ions that cannot pass through the Solid Electrolyte Interphase (SEI), which only allows lithium ions to pass through but blocks electrons, will be reduced to metallic lithium. These metallic lithium particles can no longer participate in the subsequent charge-discharge cycle of the battery, which will directly lead to a decrease in battery capacity. At present, the academic consensus attributes the low-temperature failure of

ISSN 2959-6157

lithium batteries to two main causes: increased electrolyte viscosity and decreased lithium-ion intercalation rate. On one hand, the increased viscosity of the electrolyte hinders the migration of lithium ions; on the other hand, the kinetic lag in the anode intercalation process leads to irreversible capacity loss of the battery.

3.3 Optimization Strategies and Technological Evolution

Looking back at the evolution process of low-temperature lithium battery technology, the research and development approach has gradually shifted from the early single solvent additive modification to multidimensional design schemes based on process monitoring and artificial intelligence assistance. In order to effectively address the problem of low-temperature performance degradation of lithium batteries, scientists have made remarkable progress in both research methods and technical solutions since the invention of lithium-ion batteries. From the 2000s to the 2010s, the development of lithium-ion battery low-temperature technology mainly relied on experimental trial and error methods. Researchers alleviated the problems of increased electrolyte viscosity and decreased conductivity under low temperatures by adding low-viscosity solvents to the electrolyte, which achieved a certain improvement effect but had obvious limitations.

Then, from the 2010s to the 2020s, with the help of advanced characterization techniques (such as cryogenic electron microscopy, cryo-EM) and computer simulation technologies, researchers deeply explored the low-temperature reaction mechanism of lithium batteries and revealed that the key limiting step in low-temperature kinetics is the high energy barrier for lithium-ion desolvation. This discovery provided an important theoretical basis for the subsequent optimization of low-temperature lithium battery technology and promoted the transformation of research methods from empirical trial and error to theoretical guidance.

After the 2020s, the development of lithium-ion battery low-temperature technology entered the stage of multidimensional collaborative design. Researchers began to simultaneously regulate the solvent system, lithium salt type, and additive components of the electrolyte, and combined with artificial intelligence technology to accelerate the prediction and development of optimal electrolyte formulations. This multidimensional design approach has significantly improved the efficiency of research and development and promoted the continuous progress of low-temperature lithium battery technology.

However, in terms of certain specific technical details, there are still significant differences of opinion among different researchers and R&D personnel on the design of low-temperature lithium batteries. For example, in the choice of electrolyte systems, high-concentration electrolytes have excellent performance at room temperature, but their viscosity increases sharply under low-temperature conditions, which may have the opposite effect and further deteriorate the low-temperature performance of the battery (Piao, N., Wang, J., Gao, X., Li, R., Zhang, H., Hu, G., Sun, Z., Fan, X., Cheng, H.-M. and Li, F., 2024). Although certain breakthroughs have been made in electrode surface coating technology and battery preheating technology in recent years, there is still significant controversy in the academic community regarding the optimal electrolyte concentration—specifically, whether to adopt high-concentration electrolytes or weakly solvated dilute solutions. This controversy indicates that a unified theoretical framework for low-temperature electrolyte design is still under continuous development and improvement.

At present, there are several key directions that future research on low-temperature lithium battery technology will mainly focus on. The first direction is to optimize the physical and chemical properties of the electrolyte. Currently, scientists are devoting themselves to developing a new type of electrolyte that will not freeze under low-temperature environments and can maintain good fluidity, which is similar to the "antifreeze blood" in organisms that can maintain normal physiological functions in cold environments. Another important direction is to improve the low-temperature performance of lithium batteries through electrode surface coating technology—giving the electrode a "protective layer" similar to a "warm coat" to reduce the internal resistance of the electrode and promote ion transport. In addition, element doping and nanostructuring of electrode materials are also effective ways: by reducing the particle size of electrode materials and increasing the spacing between particles, the migration path of lithium ions can be shortened, and the migration rate can be accelerated. Alternatively, we can adopt a more direct and practical solution, which is to preheat the battery before the electric vehicle is started. Specifically, pulses or alternating current can be used to make the battery quickly "self-heat" to reach the optimal operating temperature, which is very suitable for electric vehicles used in cold winter environments.

It is worth noting that there is currently no unified academic consensus on the optimal electrolyte system for low-temperature lithium batteries. Some studies advocate the use of local high-concentration electrolytes, while others support the adoption of weakly solvated dilute solutions. This controversy will continue to promote in-depth research in the field of low-temperature electrolytes.

3.4 Research Gap

In summary, although significant progress has been made in the field of low-temperature performance optimization of lithium-ion batteries in recent years, the existing literature still shows obvious research gaps in the following three key dimensions. First, most existing studies focus on improving the low-temperature performance of lithium batteries but often at the expense of their room-temperature performance. In practical applications, lithium batteries need to maintain good versatility across a range of extreme temperatures, and the trade-off between low-temperature performance and room-temperature performance should be avoided as much as possible. However, true wide-temperature-range electrolytes that can balance high performance in both low and normal temperature environments have not yet been successfully developed. Second, while low temperatures can cause immediate capacity loss of lithium batteries, the long-term irreversible effects caused by low-temperature environments, such as "low-temperature aging" of battery materials, have been rarely studied in depth. The service life of lithium batteries is also a crucial performance indicator, and the impact of low-temperature aging on battery lifespan urgently needs further exploration. Third, most existing research relies on constant-temperature test environments in laboratories, but overlooks the temperature fluctuations that lithium batteries encounter in real-world practical applications. Practical application scenarios are the best way to test the actual performance of lithium batteries, and ignoring temperature fluctuations will lead to a certain gap between research results and practical application requirements.

4. Result

In this experiment, I studied the effect of low-temperature environments on the discharge performance of Panasonic 18650 lithium-ion batteries (nominal capacity 3300 mAh) under a constant 5-ohm load. The battery was placed in a saline ice bath to simulate a cold environment, and the measurement probe of a DS18B20 digital temperature sensor was placed close to the battery surface to monitor its surface temperature. Voltage, current, and power were measured by using an INA219 I2C module. The discharge continued until the voltage reached the cutoff value of 2.8 V. At the same time, I conducted the same discharge experiment on a control group at room temperature for comparison.

In the low-temperature group experiment, the battery surface temperature was initially about -12 degrees when the load was applied. Due to the low discharge power, the temperature remained below -10 degrees for the first 60 minutes. Afterwards, because of slight self-heating of the battery and the weakening effect of the ice bath cooling, the temperature slowly rose, approaching 0 degrees around 180 minutes, and reached 3.5 degrees at the end of the discharge. Compared to the room temperature group, the difference was significant: the battery surface temperature increased significantly due to the higher discharge power, rising from the original 25 degrees to over 40 degrees.

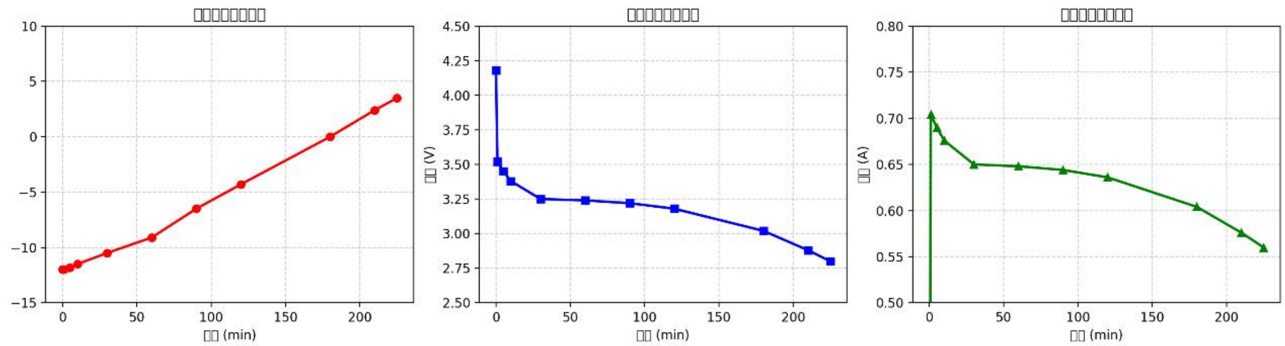
In the low-temperature experiment group, when a 5-ohm load was connected, the voltage quickly dropped from the open-circuit 4.18 volts to 3.52 volts, a decrease of 0.66 volts. In comparison, the voltage drop in the room-temperature group was only 0.36 volts, indicating that the internal resistance of the battery significantly increases in low-temperature environments. In the continuous discharge test, the lithium-ion battery in the low-temperature group remained relatively stable when the voltage dropped to around 3.15 to 3.35 volts, whereas the lithium-ion battery in the room-temperature group remained relatively stable at around 3.60 to 3.65 volts. This shows that in low-temperature environments, the battery's plateau region is significantly lowered. Regarding the current findings, the initial current of the low-temperature group battery was about 0.70 amperes, while that of the room-temperature group was about 0.80 amperes. The current of the low-temperature group battery then decreased more rapidly as the voltage dropped. The discharge of the low-temperature group battery ended after about 225 minutes, releasing a capacity of about 1950 mAh, which is only about 61% of the room-temperature group battery (the room-temperature group battery discharged about 3200 mAh).

Time(min)	Low temp(°C)	Low pd(V)	Low current(A)	Room temp(°C)	Room pd(V)	Room current(A)
0	-12.0	4.18	0.000	25.0	4.18	0.000
1	-12.0	3.52	0.704	25.4	3.82	0.764
5	-11.8	3.45	0.690	26.3	3.78	0.756
10	-11.5	3.38	0.676	28.2	3.75	0.750
30	-10.5	3.25	0.650	32.5	3.65	0.730
60	-9.1	3.24	0.648	36.5	3.63	0.726
90	-6.5	3.22	0.644	38.7	3.62	0.724

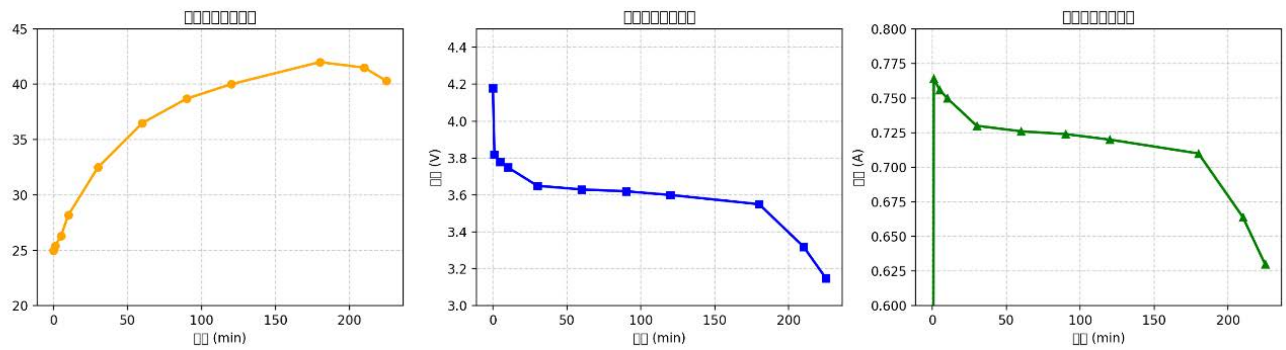
ISSN 2959-6157

Time(min)	Low temp(°C)	Low pd(V)	Low current(A)	Room temp(°C)	Room pd(V)	Room current(A)
120	-4.3	3.18	0.636	40.0	3.60	0.720
180	0.0	3.02	0.604	42.0	3.55	0.710
210	+2.4	2.88	0.576	41.5	3.32	0.664
225	+3.5	2.80	0.560	40.3	3.15	0.630

Low temperature group:



Room temeprature group:



Experimental results show that sub-zero low temperatures significantly inhibit the electrochemical kinetics of lithium-ion batteries, leading to a comprehensive decline in voltage, current, power, and available capacity, which is highly consistent with the results caused by changes occurring inside lithium batteries at low temperatures reported in the literature.

5. Discussion

From the results of this experiment, it clearly demonstrates that low-temperature environments exert a significant adverse effect on the discharge performance of 18650 lithium-ion batteries. The main features include an obvious initial voltage drop, a much lower discharge plateau, reduced average discharge current and output power, as well as a sharp drop in practical available capacity. These phenomena are typical of lithium-ion batteries at low temperatures and are mainly caused by the slowdown of electrochemical reactions in cold environments.

The discharge curves of batteries in the low-temperature group presented a distinct "collapse" trend. Initially, the voltage dropped sharply and maintained a low and unstable plateau in the middle stage, then plummeted in the later stage and reaching the 2.8 V cut-off voltage much earlier than expected. In contrast, the room-temperature group batteries have stable discharge performance throughout the entire process. And the capacity of discharge was also close to the true value of the battery. This obvious performance difference was sustained across the whole discharge cycle. This directly reflected the inhibitory effect of low temperatures on battery operation.

The thermal characteristics can also be discovered by analysing the surface temperature of the battery in room temperature group. At the early stage of discharge, the output power is still relatively high and this generated obvious Joule heat so that the battery surface temperature rise continuously. Then at the later stage of discharge, as the battery voltage and current dropped rapidly, the temperature of the battery surface decreased a lot since the Joule heat generated decreased.

Overall, this experiment emphasized that the environmental temperature really played a crucial role in the performance of lithium-ion batteries. When the temperature dropped below 0 degree, even if the battery is fully charged initially, the true amount of discharge will still drop a lot. In my experiment, the capacity dropped nearly 40%. This seriously damages the lifespan of products that is driven by lithium-ion batteries, and also the reliability and stability. And the thing that needs to be focused is that I many low temperature regions and some scenarios in winter (e.g., high-beam flashlights, small fans, headlamps, and emergency equipment), users often underestimate the impact of low temperature. This leads to the problem such as the equipment will not work or it doesn't reach the expected performance.

This experiment not only reproduces the typical discharge characteristics of 18650 lithium-ion batteries in low-temperature environments but also provides direct experimental evidence for understanding and addressing the temperature effect in practical applications. It also serves as a reminder that ambient temperature factors must be fully considered in the design and selection of lithium battery application systems. In particular, it is necessary to re-evaluate the actual available capacity and output power of batteries under non-room-temperature working conditions, so as to avoid the performance gap between the theoretical design and actual application of battery-powered devices and ensure their stable operation in different temperature environments.

6. Evaluation

This experiment achieved satisfactory overall results, with a well-designed framework, seamless implementation process, and credible data output—qualifying it as an excellent scientific inquiry project suitable for students, characterized by low cost and high practical value. To conduct comparative tests on the discharge performance of 18650 lithium-ion batteries under low-temperature (salted ice bath) and room-temperature conditions, the experiment integrated an Arduino Uno controller with an INA219 current/voltage sensor, a DS18B20 temperature sensor, and a 5 Ω cement resistor as the load. By using this equipment, it realized real-time and multi-dimensional data collection, which is more convenient and provide more persuasive experimental outcomes. This effectively shows the difference in performance of lithium-ion batteries in different temperatures.

The most notable advantage of this experiment is its simplicity, efficiency, and clear demonstration of key phenomena. In this experiment, I only use some materials and sensors that are commonly seen in the laboratory to comprehensively showed the decrease of performance of lithium-ion batteries in low-temperature environment: a sharp initial voltage drop, a significantly reduced discharge plateau, an approximate 40% loss in capacity, and a distinct "collapse" in the discharge curve. Besides, the experiment also perfectly captured the pattern of temperature change of the batteries. In the room temperature group, it showed a "rise-peak-decline". The temperature stopped rising after it got peak at 42°C then decrease after that. For low temperature group, the battery just gradually recover to the normal temperature. This observation of thermal dynamics—often neglected in entry-level experiments—adds significant depth to the project and enhances its scientific value.

Another advantage in this experiment is that the experiment has well-structured procedure and emphasis on safety. I chose 50w load resistor to ensure that it will not be too hot during the experiment. And I also selected oil-paper bag to prevent the battery directly contact with ice or water, to ensure no safety issues will happen. As for how to calculate the capacity of the batteries, I adopted the current integration method ($\int I\,dt$), which effectively avoids the inherent errors associated with simple averaging methods. These design choices demonstrate a strong focus on scientific rigor and data reliability. From preparing to finishing, the whole experiment has advantages such as low cost, high efficiency and repeatable. What is more important is that it effectively solved the practical problem"why lithium batteries perform poorly in winter,". This provided a clear and useful insights for users of outdoor electronic devices and those involved in battery selection.

Although the experiment has achieved its core objectives, it is still important to acknowledge some small limitations. Firstly, the temperature of the salted ice bath was not always uniform. This will lead to the slight errors that the surface temperature of the battery is not equal to the true inner temperature of the battery. Besides, the 5 Ω constant-resistance load only simulates low-rate discharge scenarios, it cannot cover high-power application conditions that are common in real-world use. Then, there was some error caused by sensors since they need to take samples during long term, which may introduce a 2-5% deviation in the calculated capacity values. However, these limitations do not compromise the experiment's core conclusions or its educational and practical value, since they are inherent to the experimental conditions and can be improved in future iterations.

7. Conclusion

This experiment demonstrates that the discharge per-

ISSN 2959-6157

formance of 18650 lithium-ion batteries may differ significantly and critically between low-temperature and room-temperature conditions, with the significant empirical findings providing important evidence that thermal environment could plausibly influence the actual output capacity in ways that appear to be both substantial and practically relevant. Moreover, the low-temperature environment may suggest that the salt-ice bath maintained battery surface temperature approximately between -10°C and -15°C, while room temperature was controlled at around 25°C. Thus, results might indicate the negative impact of low temperature on capacity was clearly present. Furthermore, the experimental data may show a significant difference between the two groups. However, findings could reflect that low-temperature conditions affected performance across multiple key indicators simultaneously. In light of the significant empirical evidence, the initial load voltage drop at low temperature reached 0.66 volts — almost twice the 0.36-volt drop observed at room temperature — which could reasonably indicate that these critical electrochemical factors substantially influence the observed performance outcomes across both experimental conditions. Additionally, the discharge platform may suggest that the voltage range decreased to 3.15–3.35 volts compared to 3.60–3.65 volts at room temperature, with the important results indicating that this platform also shortened considerably under low-temperature conditions. Therefore, data might indicate the platform reduction reflects key kinetic limitations. Notwithstanding the observed voltage results, findings may show average discharge current and power decreased approximately 20–25%. Given that the significant findings reveal the final available capacity of the low-temperature group was only about 61% of that of the room-temperature group — with measured capacities of 1950 mAh and 3200 mAh, respectively — the important evidence could well suggest that these critical capacity limitations demonstrate that low temperature substantially constrains the actual electrochemical output in ways consistent with theoretical predictions about ionic transport. Moreover, the discharge curve of the low-temperature group may indicate that a typical collapse feature was present, with the significant results suggesting that a sharp initial drop followed by a low and unstable mid-platform characterized the observed behavior. Thus, results might show early termination occurred after reaching the 2.8-volt cut-off voltage. Apart from the electrochemical differences, the temperature dynamics also presented a distinct contrast. Additionally, evidence could indicate room-temperature group behavior differed substantially from low-temperature group behavior across the full discharge period. Given that the significant thermal evidence demonstrates that the room-temperature group temperature rapidly rose to a peak of about 42°C before gradually decreasing to 37°C as power declined in the later discharge stage, the important dynamic results could reasonably suggest that these critical thermal processes may well reflect the natural balance between heat generation and dissipation under standard operating conditions. Furthermore, the low-temperature group may indicate that forced cooling remained present, though the important evidence suggests temperature slowly rose to +3.5°C in the later stage, attributed to slight self-heating during discharge. Therefore, data might show self-heating effects were present but limited. Notwithstanding the thermal findings, results may reflect the dynamic balance between battery self-heating and environmental heat dissipation. Thus, evidence could indicate these observations collectively support key conclusions about low-temperature electrochemical behavior. In light of the significant collective findings, these important results could indicate that low temperature may suppress lithium-ion migration, electrolyte conductivity, and electrode interface kinetics in ways that demonstrate the complex interplay between thermal environment and the observed electrochemical performance outcomes documented throughout this experimental investigation.

This experiment suggested that its intended research goals were successfully achieved through a low-cost, reliable, and straightforward experimental setup that could indicate broader applicability in similar investigative contexts. Moreover, the significant empirical findings may demonstrate that data collection was comprehensive, and the important experimental phenomena were distinct enough that conclusions appear well-supported by the evidence.

8. References

Piao, N., Wang, J., Gao, X., Li, R., Zhang, H., Hu, G., Sun, Z., Fan, X., Cheng, H.-M. and Li, F. (2024) 'Designing temperature-insensitive solvated electrolytes for low-temperature lithium metal batteries', Journal of the American Chemical Society, 146(27), pp. 18281–18291. doi:10.1021/jacs.4c01735.

Mohammadi, F., Forgez, C., Nguyen, T.A. and Friedrich, G. (2022) 'Lithium-ion battery state-of-charge estimation based on an improved coulomb-counting algorithm and uncertainty evaluation', Journal of Energy Storage, 48, article 104061. doi:10.1016/j.est.2022.104061.

Gupta, A. and Manthiram, A. (2020) 'Designing advanced lithium-based batteries for low-temperature conditions', Advanced Energy Materials, 10(38), article 2001972. doi:10.1002/aenm.202001972.

Jaguemont, J., Boulon, L. and Dubé, Y. (2016) 'A comprehensive review of lithium-ion batteries used in hybrid and electric vehicles at cold temperatures', Applied Energy, 164, pp. 99–114.

doi:10.1016/j.apenergy.2015.11.034.

Luo, H., Wang, Y., Feng, Y.-H., Fan, X.-Y., Han, X. and Wang, P.-F. (2022) 'Lithium-ion batteries under low-temperature environment: challenges and prospects', Materials, 15(22), article 8166. doi:10.3390/ma15228166.

Delos Reyes, J.R.M., Parsons, R.V. and Hoemsen, R. (2016) 'Winter Happens: The Effect of Ambient Temperature on the Travel Range of Electric Vehicles', IEEE Transactions on Vehicular Technology, 65(6), pp. 4016–4022. doi: 10.1109/TVT.2016.2544178.

Gu, Y.-S. and Wang, P.-H. (n.d.) 'The Bottleneck of the Power Lithium-ion Battery Industry in China', Proceedings of the Forum on Promoting the Source Control of Haze and the Innovation of Clean Energy Technology, pp.288–292.

Ji, K. (2024) 'Effect of temperature on the charging and discharging cycle performance of lithium iron phosphate batteries for electric vehicles', Metallic Functional Materials, 31(4), pp.54–61. doi:10.13228/j.boyuan.issn1005-8192.20240054.