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Article

Study of temperature cycling of commercial rechargeable lithium-ion batteries

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ABSTRACT

Lithium-ion batteries, a popular electric energy storage device, have high energy density and impressive working performance. However, the temperature affects its life cycle, capacity, and performance. Different effects are generated inside the battery for the different temperature conditions. It is necessary to study their thermal and electric characteristics in various thermal conditions since electric energy storage devices are used in various applications at low or high temperatures. In this study, the experimental analysis was performed to observe how a battery cell behaves above room temperature for a different 18650 cylindrical battery cell with a capacity of 5200 mAh. The testing temperature for this experiment was at 28°C, 50°C, 60°C, 70°C, and 100°C. It is noted that the capacity of the battery cell fades drastically at high temperatures compared to low temperatures due to internal short circuits occurring at high temperatures.

1. Introduction

A battery, an energy storage device, is one of the most important parts of electrical gadgets, where electrochemical reactions occur and produce electricity [1, 2]. The battery business went through an evolution when Sony Corporation unveiled the first commercial LIB in 1991 [3]. An anode made of carbon, a cathode based on lithium compounds, an electrolyte, and a separator make up a typical LIB. The majority of studies into LIBs have focused on identifying the optimum electrode material in terms of specific energy, cycle life, capacity, and power, with little emphasis devoted to temperature control [4]. At high temperatures, LIBs performance degrades due to thermal runaway, aging, etc. Feng et al. [5] observed in their experiment that at high temperatures, the rates of deterioration of all LIB components increase. However, on the other hand, at low temperatures due to low kinematics, the battery performance is found limited [6]. Hence, it is very important to study the temperature effect on a lithium-ion battery and find an optimum safe operating temperature range. Complex electrochemical changes take place during the charging and discharging of a LIB with a significant amount of heat release. The performance, longevity, as well as safety of a Lithium-Ion battery, are affected by the operating or ambient temperature [7, 8]. In addition, temperature affects the ionic conductivities of electrodes and electrolytes [9]. The properties of electrolytes are affected when the battery is exposed to cold temperatures. At low temperatures, the internal resistance of the electrolyte rises due to its viscosity. As a result, the Lithium-ion diffusivity and the electrolyte's ionic conductivity, power, and capacity of the cell decrease [10–12]. The charge transfer resistance (Rct) is one of the most significant factors that also increases at low temperatures [6]. Zhang et al. interpreted in their experiment that it is more difficult to charge a drained Li-ion battery than it is to discharge a charged battery at a low temperature [6]. Petzl et al. [13] demonstrated that at low temperatures, lithium plating occurs. Lithium plating can penetrate separators and reduce capacity. These lithium dendrites, which are located on the surface of the negative electrode of LIBs, cause an internal short circuit [14]. However, high temperatures impair the performance of Lithium-ion batteries more than low temperatures. At room or standard operating temperature, electrochemical reactions and charge transfer produce heat inside the battery [15]. Irreversible processes such as heating due to mixing, polarization, enthalpy change, etc. are also responsible for generating heat. Xiao and Choe proposed a completely new heat generation formulation, which incorporates enthalpy heating and heat of mixing [15]. The Thermal Runway is another destructive phenomenon for a lithium-ion battery. It occurs when the heat formed inside a battery surpasses the quantity of heat released to its surroundings [16]. In Figure 1 thermal runaway process of a LIBs cell is illustrated. At high temperatures, exothermic reactions occur in the battery, and uncontrollable heat is produced. In addition to that, internal pressure is increased due to the production of some gaseous elements. As a result, exploration would occur [17]. Feng et al. [18] observed that during thermal runaway, the internal temperature was increased above 870˚C, and the temperature difference was approximately 520˚C inside the tested battery. Depending on the battery cells' chemistry, charge level, and the exothermic processes that cause thermal runaway have different onset temperatures. Typically, the lower the initiation temperature for thermal runaway, the greater the cell voltage or state of charge [19].

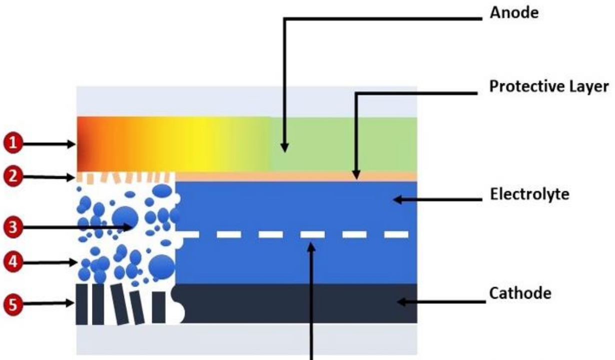
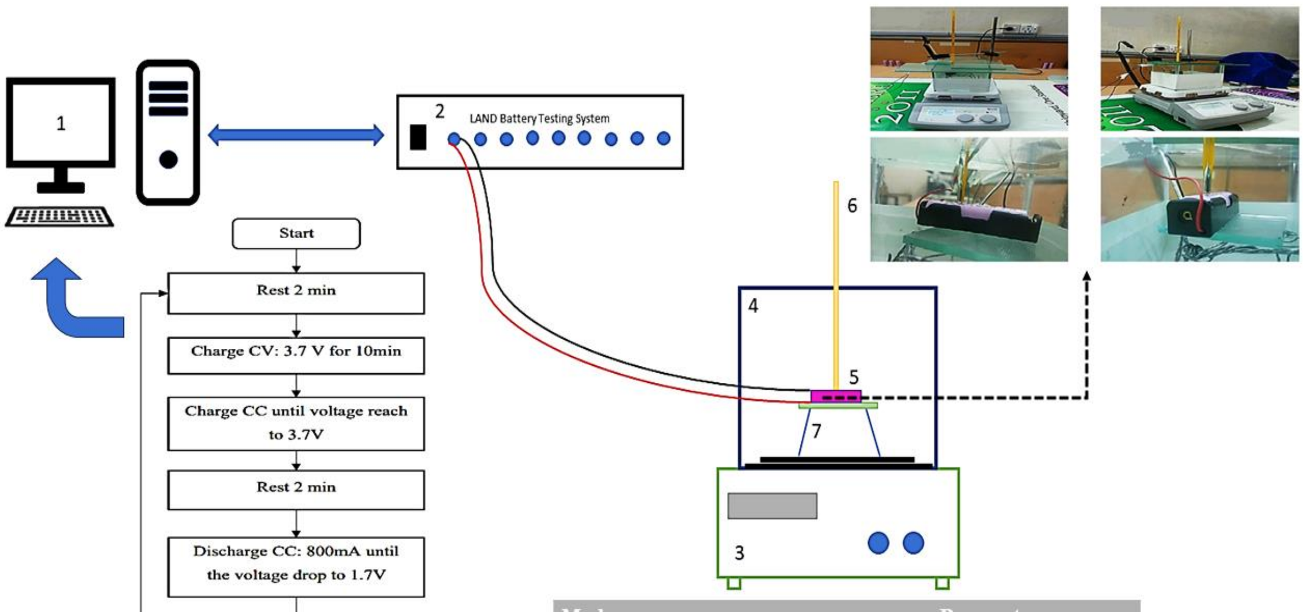


Figure 1. Lithium-ion battery cell's thermal runaway process (Here numbers represent: 1-heating begins, 2-protecting layer disintegrates, 3-flammable gas is formed when electrolytes break, 4-Separator melts may result in short circuits, 5-cathode disintegrates and produces Oxygen)

At high temperatures, LIB's lifespan, as well as performance, are reduced due to aging. Leng et al. found by their investigation that when a Sony Prismatic lithium-ion battery was aged from 25˚C to 55˚C, its capacity decreased due to the temperature effects [20]. The measuring techniques of a battery's internal temperatures are more convoluted compared to the surface temperature due to its multilayered structures. However, using thermocouples and thermal imaging systems, the surface temperature of LIBs can be easily measured [21]. To detect the temperature by contact measurement, temperature sensors such as Fiber Bragg Grating (FBG) sensors or thermocouples are placed within LIBs. However, the structural integrity of LIBs can be damaged by the insertion of heat sensors [22]. That's why electrochemical impedance-based and modeling simulation techniques are developed to eliminate the damage to the internal structure of the LIBs. The thermal model and the thermal-electric model are the two numerical models that were developed by the researchers for determining the internal temperature of LIBs. In the thermal model, only thermal and in the thermal-electric model, thermal as well as electric characteristics inside batteries can be predicted [23, 24]. Electrochemical Impedance Spectroscopy (EIS) is another technique for determining the electrochemical impedance of an electrochemical system using a frequency-varying sinusoidal current. The internal temperature and SOC of LIBs can be monitored using EIS simulation software [25]. It is noted that a lithium-ion battery's life cycle, performance, power, capacity, and other properties are all influenced by temperature.



Mode	Parameters
Maximum cutoff voltage	3.7 V
Minimum cutoff voltage	1.7 V
Charging	800 mA
Discharging	800 mA
Cycles	20

Figure 2. Schematic diagram of the experimental setup (here number represents: 1-Desktop Computer, 2-LAND Battery testing system, 3-Magnetic stirrer with a hot plate, 4-Glass box, 5-18650 cylindrical Li-Ion Battery, 6-Thermometer, and 7-Stand)

There is a chance to develop new technologies that would reduce the impact of temperature on LIBs, and the performance of the LIBs can be enhanced by using different nanomaterials and porous materials as the anode of LIBs [2,26–32]. Additionally, studying how temperature affects LIBs is essential for security concerns. In this study, the cycling behaviors of a '18650 Lithium-Ion Battery' cell under different temperature conditions are explored experimentally. In the battery industry, performing experiments at a high temperature is a challenging task and highly sought-after. The battery has been tested at 28°C, 50°C, 60°C, 70°C, and 100°C. The properties of the battery obtained at higher temperatures are compared with the properties obtained at room temperature.

2. Experimental setup

The investigation was carried out to study the cyclic performance of 18650 cylindrical Li-ion battery cells according to a systematic process, which is illustrated in Figure 2. The maximum capacity of the cell was 5200mAh. During the experiment, the battery cell was connected to the "LAND" battery testing system. Initially, the data were collected at room temperature. Then, the heater was turned on to create an environment above the room temperature to collect data at 50°C, 60°C, 70°C, and 100°C. The heater was enclosed with a glass box to maintain a constant temperature. To measure the temperature, a thermometer and a thermocouple were set near the battery. Batteries charging and discharging were controlled by the LAND Battery testing system.

3. Results and discussion

Figure 3 illustrates the typical V-t and I-t curves of twenty cycles for a Li-ion battery in the charge-discharge test at room temperature (28°C), where the red color line indicates the voltage change and the blue color line indicates the current change during the cycling. From the beginning to the end of the charging-discharging operations, there were four sudden voltage (V) fluctuations occurred in each cycle, which is illustrated in Figure 4.

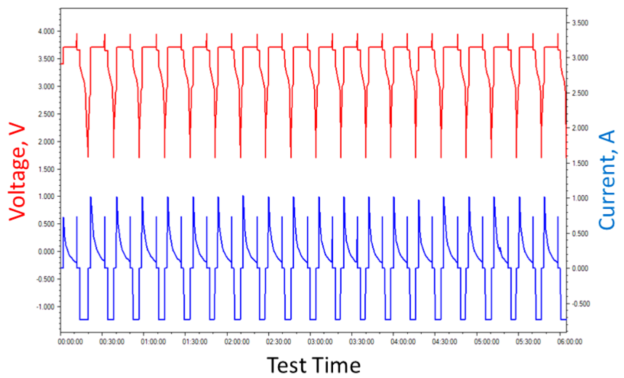


Figure 3. Voltage and current vs. test time at room temperature (28°C)

At the very beginning, when a new charge-discharge cycle starts, the cell is first charged at a constant voltage of 10 minutes. Then sudden voltage peak arises during a constant current charging condition. A micro-level internal short circuit may have occurred at this moment. After the charging process was complete, the constant current discharge process began. Voltage dropped gradually at this stage. During the rest period of the cell of 2 minutes, the voltage was increased from 1.7V to 2.5V.

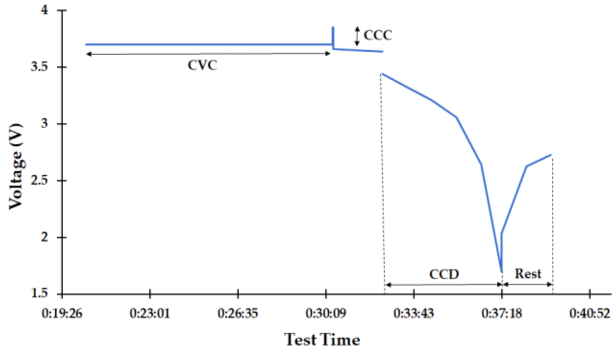


Figure 4. Voltage changes over time for one cycle

Figures 5 to 7 illustrate the discharging voltage versus capacity change of the battery cell at 28°C, 50°C, 60°C, 70°C, and 100°C, respectively. For each case, the voltage range was between 1.7V to 3.7V; however, the capacity change was different. Figure 5 depicts the discharging data of a fully discharged cell that was kept at room temperature and 50°C. From cycle 1 to 20, capacity was fading slowly when the cell was at room temperature, which is shown in Figure 5(a). After analyzing Figure 5 (b), it can be said that, during the first cycle of discharging, the capacity of the cell was around 75mAh. But, from the first cycle to the second cycle, capacity fades almost 25%. Analyzing the curves of the discharging voltage from Figure 6 to 7, it can be said that above the room temperature, the battery's capacity decreased by almost 66.67%, 75%, and 77% from the first cycle to the second cycle when the cell temperature was 60°C, 70°C and 100°C, respectively. The capacity-reducing phenomena may have occurred due to the Solid Electrolyte Interphase (SEI) layer formation in the anode [31–33], or maybe the Li-ion did not get enough time to move from one electrode to the other during the cycling operation. When the cell was discharged at 100°C temperature, the internal short circuit occurred at the 16th cycle shown in Figure 7. A large capacity drop was observed between cycle 15 to cycle 17. The cell slightly recovered its lost capacity after the internal short circuit from cycle 17.

Figure 8 depicts the discharging voltage over capacity at cycles 1,10 and 20. It also demonstrates that there is a large capacity gap between the first and the last cycle. However, the capacity difference gap decreases when the temperature gets higher and higher between cycle 10 and cycle 20. Figures 9 to 10 depict the charging and discharging capacity and efficiency vs. cycle number at room temperature (28°C), 50°C, 60°C, 70°C, and 100°C, respectively. The efficiency discussed here is the Coulombic efficiency, also known as Faradaic efficiency. It is defined as the total charge extracted from the battery to the total charge put into the battery over a full cycle. For each case, the Coulombic Efficiency (CE) was escalated above 100%. Figure 9(a) depicts that the charging and the discharging capacity fades gradually when the cell is at room temperature, although the efficiency increases slightly. From Figure 9(b), it can be concluded that the cell behaves anomalously when it is at 50°C. At cycles 8 and 16, the Coulombic Efficiency suddenly increased. Figures 9(c) and 9(d) exhibit the cyclic performance at 60°C and 70°C, respectively.

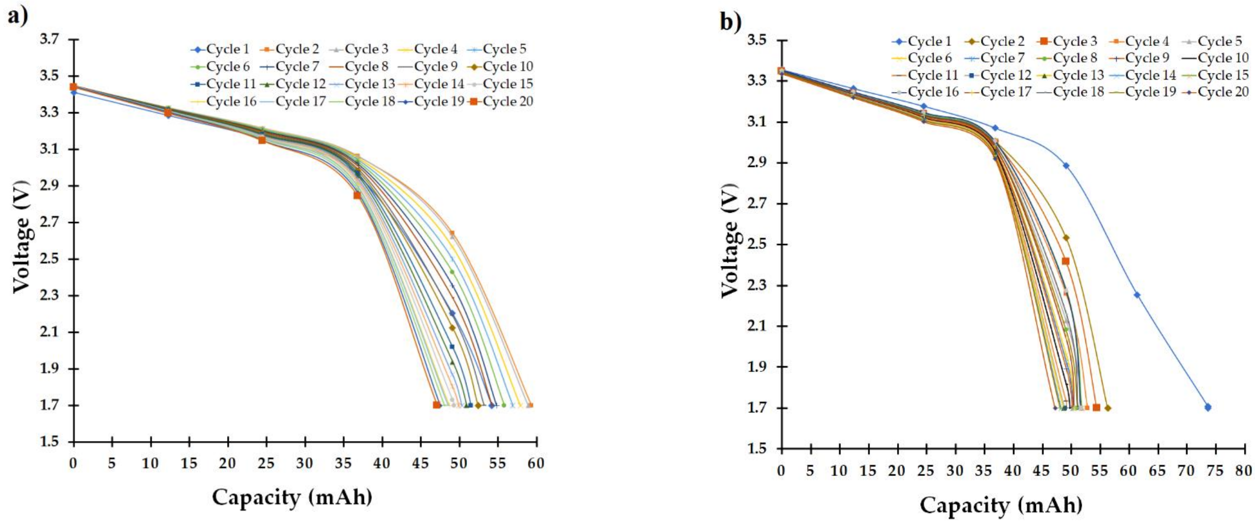


Figure 5. Voltage and Capacity change during discharging at (a) room temperature and (b) 50˚C

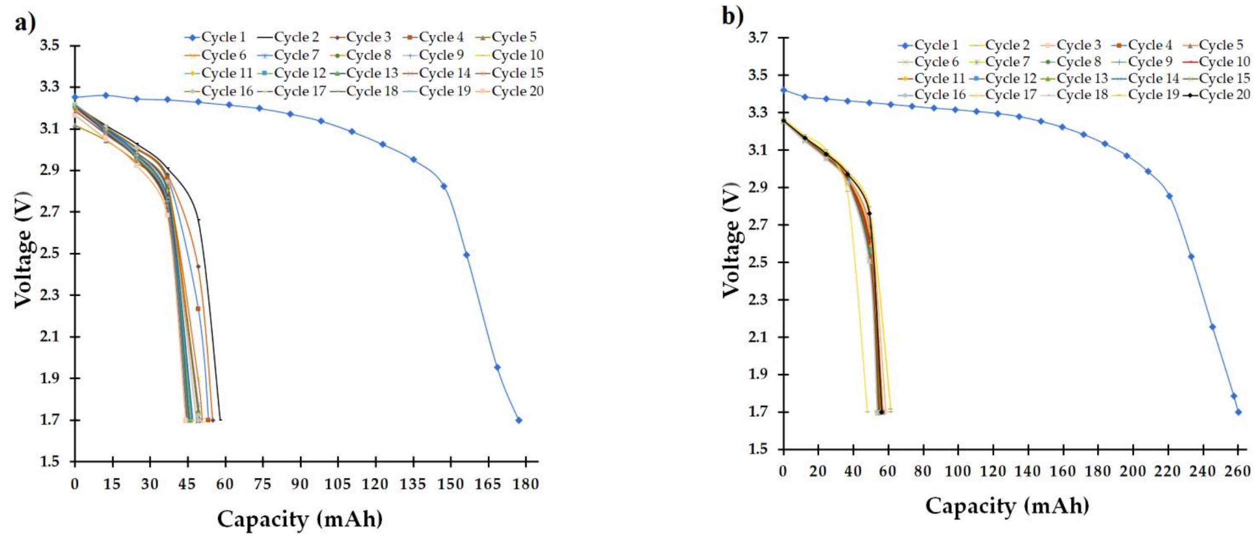


Figure 6. Voltage and Capacity change during discharging at (a) 60˚C and (b) 70˚C

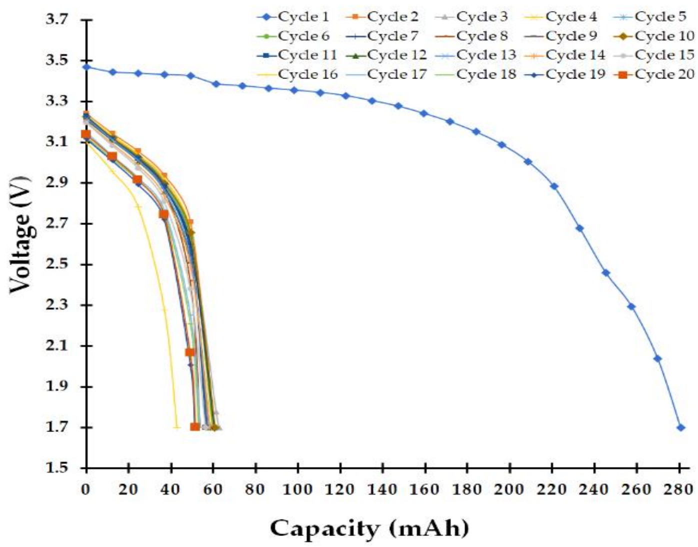


Figure 7. Voltage and Capacity change during discharging at 100˚C

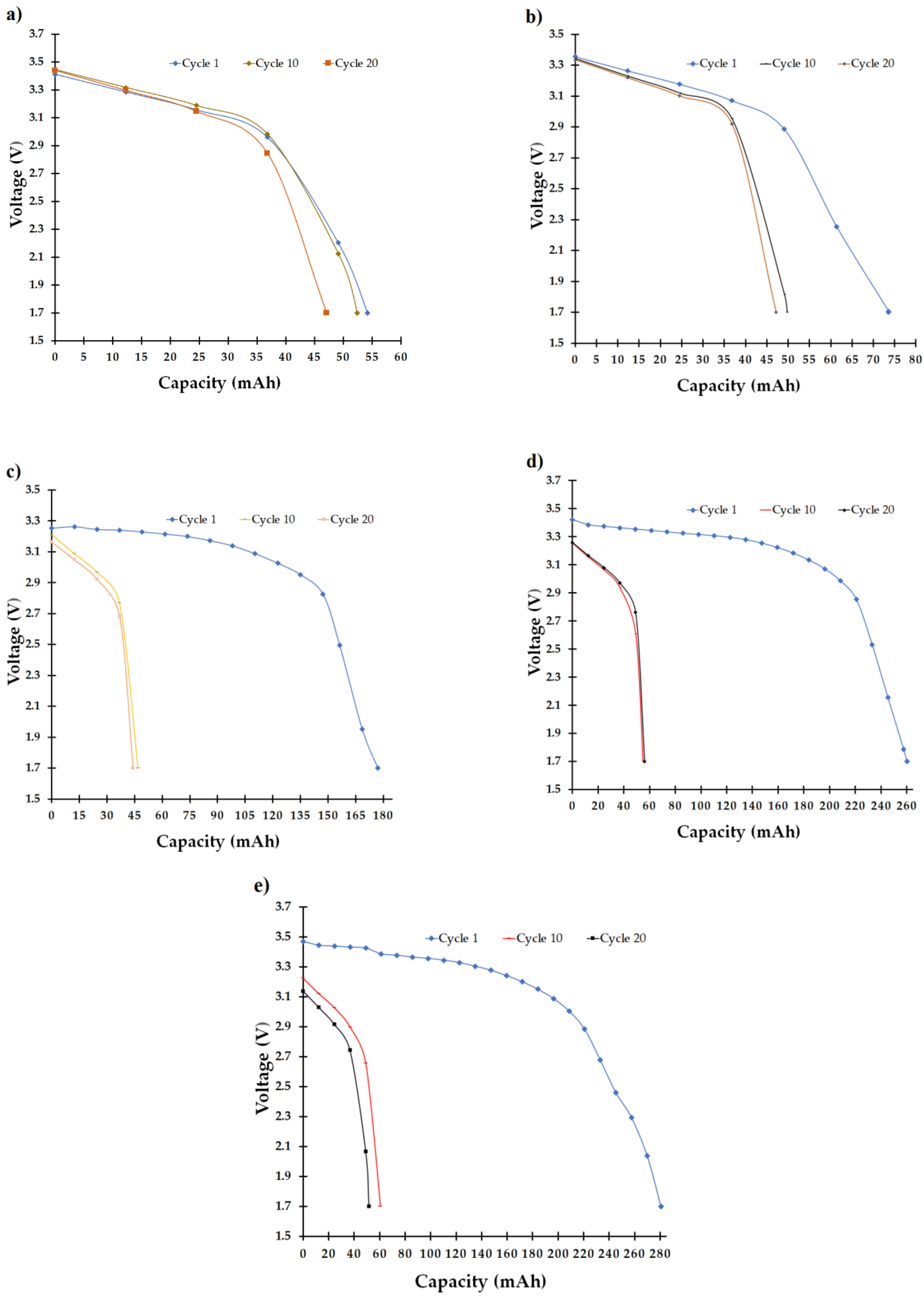


Figure 8. Discharging Voltage vs Capacity of cycles 1, 10, and 20 at (a) Room temperature (b) 50°C (c) 60°C (d) 70°C (e) 100°C

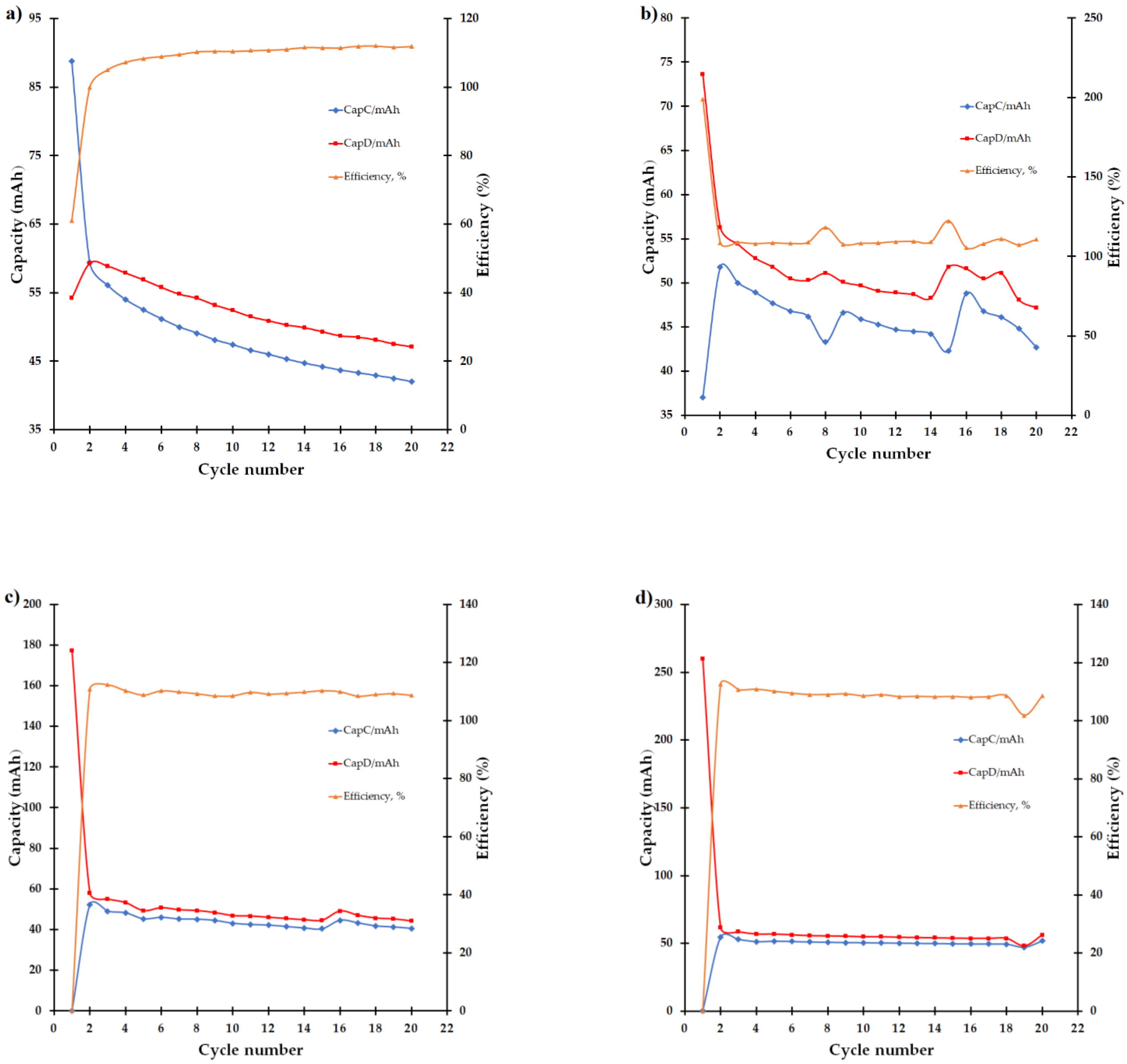


Figure 9. Cyclic performance at (a) room temperature, (b) 50˚C, (c) 60˚C, (d) 70˚C

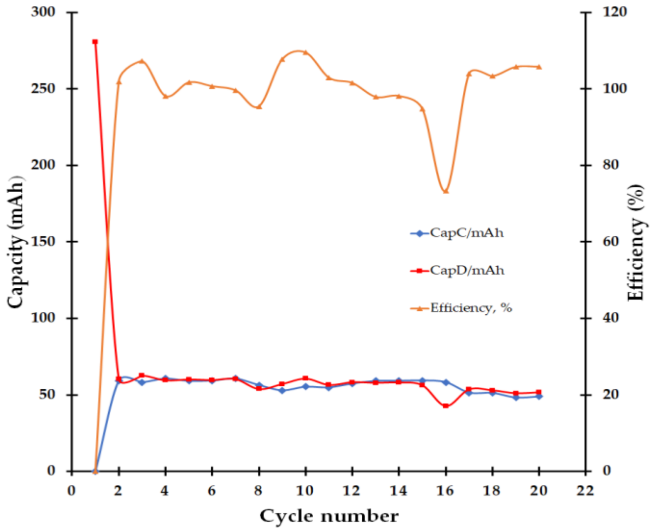


Figure 10. Cyclic performance at 100˚C

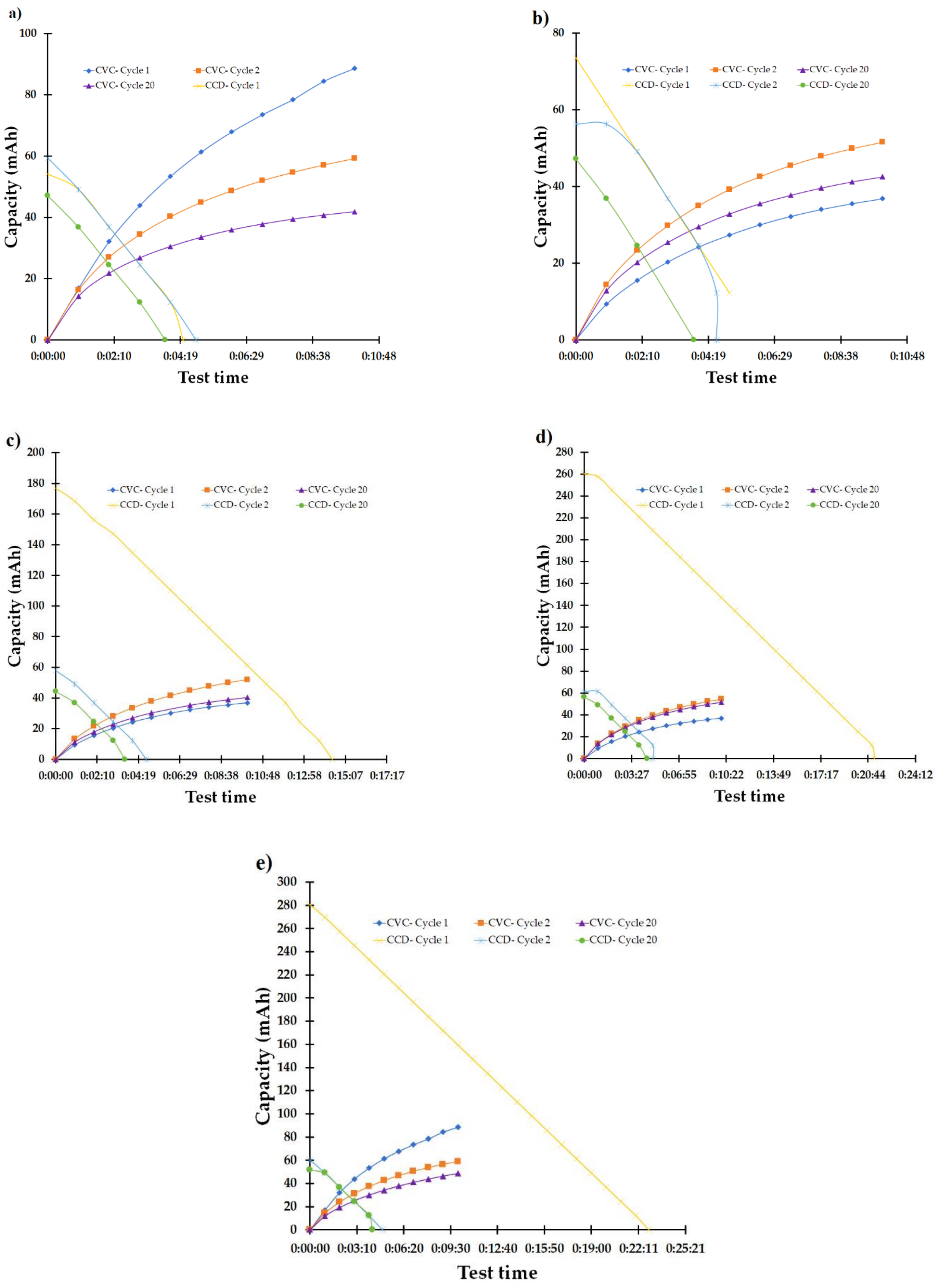


Figure 11. CVC, CCD for cycles 1,2 and 20 at (a) Room temperature (b) 50˚C (c) 60˚C (d) 70˚C (e) 100 ˚C

A sudden pick was observed during the 16th cycle when the cell was at 60˚C. But a sudden drop was observed during the 19th cycle for 70˚C. The discharging capacity, as well as the charging capacity, changed in this case. These may have occurred due to the internal short circuit that occurred inside the battery cell. At high temperatures, the electrolyte may be decomposed by the exothermic reaction; as a result, an internal short circuit of a battery occurs when the two electrode materials are internally and electronically interconnected, resulting in high local current densities. These Internal short circuits in lithium-ion batteries can happen as a result of lithium dendrite formation or a compressive shock [31]. The battery cell behaves also anomalously when it was cycling at 100˚C, which is represented in Figure 10. A sudden increase and decrease in Coulombic efficiency were observed. Some major abnormality was seen in cycles 4, 8, and 16. This phenomenon may have happened due to an internal short circuit inside the battery cell [31]. The battery's internal exothermic reaction, as well as the environmental high temperature, were responsible for the internal short circuit. The cell capacity may be decreased due to the internal short circuit or other phenomena inside the battery cell, such as severe volume changes during lithiation and de-lithiation, resulting in inadequate cyclability and ultimate electrode failure [29]. This phenomenon also affects the performance as well as the cycle life of the battery cell. From Figure 11, it can be concluded that the battery discharged rapidly at the 20th cycle compared to the 1st cycle.

4. Conclusion

The charging and discharging characteristics of a Li-ion battery for 20 cycles at different temperatures have been analyzed. Observing how a battery cell behaves above room temperature was the main purpose of this study. The findings of this study can be concluded as follows:

• From the temperature of 50˚C to 100 ˚C, there was a sudden capacity drop observed between the first and the second cycle.

• During charging at a constant current, a sudden voltage peak was detected. This phenomenon occurs due to the micro-level internal short circuit.

• Discharging Capacity faded above the room temperature. The range of the capacity decreased from the first to the last cycle as the cell was exposed to a higher temperature.

• Internal Short Circuit occurred above 70˚C. These may occur due to the decomposing of the electrolyte for an exothermic reaction.

• The lifetime of the cell decreased at higher temperatures.

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Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Conflict of interest

The authors declare no potential conflict of interest.

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